



## **Enabling Mass Customization in Engineer-To-Order Industries**

A multiple case study analysis on concepts, methods and tools

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# Enabling Mass Customization in Engineer-To-Order Industries

A multiple case study analysis on concepts, methods and tools



**PhD thesis 2.2015**

**DTU Management Engineering**

Martin Bonev  
January 2015

*To my family and all my teachers, professors and supervisors throughout my academic career, from the elementary school in Sofia and the three schools in Hanover, to the four universities in Hanover, Tokyo, Cambridge, and Kongens Lyngby*

*I Cannot Teach Anybody Anything, I Can Only Make Them Think.*

- Socrates



# DECLARATION

This dissertation is the result of my own work and includes nothing, which is the outcome of work done in collaboration except where specifically indicated in the text. It has not been previously submitted, in part or whole, to any university or institution for any degree, diploma, or other qualification.

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## ABSTRACT

Choosing goods and services that satisfy individual needs has become possible in many consumer markets today. Technological advancement in sales and production enabled a variety of products, from automotive to apparel, to be mass customized in a profitable manner. Over time, these companies learned to handle the negative impact of a resulting increase in architecture complexity. In contrast, engineer-to-order firms, whose core business is to create bespoke product variants engineered to specific needs, could not benefit to the same degree from the progress towards mass customization. Though customizing engineering products has a wide-ranging impact on companies' architecture. The interconnected and hardly standardized design combined with highly varying processes makes the specification and fulfilment of customization requests difficult to handle. Moreover, although likewise affected with rising complexity levels and stronger customization responsiveness, their challenges and motivations towards mass customized solutions have seldom been discussed.

To address this challenge, this thesis elaborates on state-of-the-art research in architecture design and specification processes development and defines general capabilities to facilitate mass customization in engineer-to-order firms. The established understanding is complemented with interviews of practitioners from 18 engineering companies to obtain further insight into essential aspects of the research field. Based on the gained experience, eleven empirical studies have been conducted to develop relevant concepts and methods aiming at enhancing the identified capabilities. This close collaboration with industries ranging from construction to process plants and machinery applications promoted the development of a practical tool, termed Integrated Design Model (IDM). The IDM tool integrates adjacency matrixes, node-link diagrams and generic modelling methods, to improve the explicitness and visibility of architectures. Connected to advanced expert systems, such as product configuration systems, the tool enables a formalized procedure for managing the design of complex architectures using aspects of visual analytics and computational structural analyses.

Finally, the evaluation of the obtained results indicates a strong managerial and theoretical potential for the establishment of mass customization in engineer-to-order industries and pinpoints areas for further investigation.

## DANSK RESUMÉ

Valg af varer og ydelser, der opfylder særlige individuelle behov, er i dag muligt inden for mange forskellige markeder. Med den teknologiske udvikling inden for marketing og produktion, kan produkter fra såvel bilindustri til tekstiler specialfremstilles gennem masseproduktion på en profitabel måde. Industrien har gennem tiderne lært at håndtere den negative effekt af stigende kompleksitet inden for arkitektur. I kontrast dertil står 'engineer-to-order'-virksomheder, hvis primære forretning går på at skræddersy specifikke løsninger til kunden. Sådanne virksomheder har ikke kunnet drage en tilsvarende fordel af udviklingen imod en større grad af masseproduktion af specialfremstillede produkter. Kundetilpasning af tekniske produkter har en stor påvirkning på virksomheders arkitektur. Designprocesserne for et givent produkt er typisk unikt sammenkoblede, og har ikke-standardiserede forløb, hvilket resulterer i vanskeligheder med hensyn til kravspecifikationer og indfrielse af kundetilpasning. Virksomhedernes udfordringer og motivation til kundetilpassede mass customized løsninger er sjældent blevet beskrevet, selvom disse virksomheder på samme måde er påvirket af stigende kompleksitet og højere krav til reaktionsevnen for kundetilpasning.

Dette Ph.d.-projekt belyser den nyeste forskning inden for arkitekturdesign, procesudvikling inden for kravspecifikationer og samler viden om dette ved at definere generelle evner til at facilitere kundetilpasning af produkter i 'engineer-to-order'-virksomheder. Forståelsen for disse emner understøttes af interviews med fagfolk fra 18 ingeniørvirksomheder for at opnå en dybere indsigt i essentielle aspekter af researchområdet. Baseret på den indsamlede viden fra interviewene, er der udført 11 empiriske studier med formålet at udvikle relevante koncepter og metoder, der kan forbedre de identificerede emneområder. Det tætte samarbejde med de industrielle parter, som spænder fra byggeri til maskinapplikationer munder ud i udviklingen af en praktisk løsning, kaldet Integrated Design Model (IDM). IDM løsningen integrerer adjacency matricer, node-link diagrammer og generiske modelleringsmetoder for at forbedre overskueligheden af produkt arkitekturen. Løsningen kobles til eksisterende avancerede ekspertsystemer såsom produktkonfigurationssystemer, hvilket muliggør en formaliseret procedure til at håndtere opbygningen af komplekse produkt arkitekturer ved brug af visuelle analyse- og beregningsmæssige strukturelle analyser.

Evaluerings af de opnåede resultater indikerer et stærkt ledelsesmæssigt- og teoretisk potentiale for etablering af mass customization i 'engineer-to-order'-virksomheder. Ligeledes bliver fremtidige forskningsmuligheder fremhævet.

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## LIST OF ABBREVIATIONS AND ACRONYMS

ABC	Activity-based costing
AD	Axiomatic design
ATO	Assembly-to-order
ATO <sub>ED</sub>	Adapt-to-order
BOM	Bill of material
CAD	Computer aided design
CM	Contribution margin
CS	Configuration system
CTO <sub>ED</sub>	Configure-to-order
DMM	Domain mapping matrix
DRM	Design research methodology
DSM	Design structure matrix
EBIT	Earning Before Interests and Taxes
ETO	Engineer-to-order
ETO <sub>ED</sub>	Engineer-to-order
ETS <sub>ED</sub>	Engineer-to-stock
GM	Gross margin
GVM	Geometric variant master
IDM	Integrated design method
IT	Information technology
KBE	Knowledge-based engineering
KPI	Key performance indicator
MC	Mass customization
MFD	Modular function deployment
MTO	Make-to-order
MTS	Make-to-stock
NPD	New product development
OCL	Object constraint language
PFMP	Product family master plan
PVM	Product variant master
QFD	Quality function deployment
RQ	Research question
SEM	Stakeholder evaluation matrix
UML	Unified modelling language

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# 1 INTRODUCTION

## 1.1 Motivation

### 1.1.1 Why product customization matters

*„It is my belief that the ‘mass market’ is dead - segmentation has now progressed to the era of mass customization“* (Kotler, 1989). What Kotler expressed already in 1989 still so clearly records an ongoing and rapid development of consumer markets within the last decades. The post-war years dominated until the 60s the largely unsaturated markets with the need to catch up with consumption and a growing population. The established concepts of Frederick W. Taylor and Henry Ford satisfied strong demands with the efficiency of anonymous mass production. In the late 60s, this extensive saturation finally translated into the emergence of small to very small niche markets, which in the late 80s resulted in an extremely pronounced segmentation of the entire developed region (Davis, 1989). More recently, the demand towards higher product variety and customization has been increasing even further. As studies have shown, a general trend for more individual goods and services can nowadays be observed within the majority of commercial and industrial sectors alike (Fogliatto et al., 2012; Funke and Ruhwedel, 2001; Klenow and Bils, 2001). The *customization* of products hereby describes the process of configuring a valid product design by selecting feasible compositions of somewhat predesigned components within a predetermined scope of the offered variety (ElMaraghy et al., 2013). It includes activities related to specifying a valid product design, which fits to the given requirements.

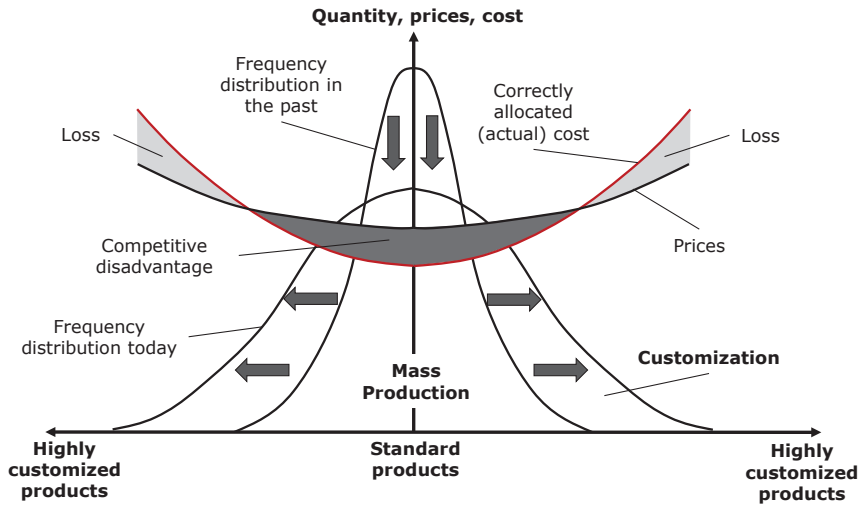
Today’s motivations for further customization are diverse and may be both market and technology driven. However, the basic driver remains the same. Acting upon saturated markets, companies aim at obtaining higher customer value and stronger economic benefits through rapidly responding to individual needs. On the other hand, as technologies evolve, new material, designs and services are being developed, the concept of customization is being employed as an important business strategy to stay competitive and to attract more buyers (Piller et al., 2004). Regardless the individual impulse, customization requires from providers to seek innovation and to utilize new technologies in order to differentiate with a wider range of choices. In doing so, companies can offer unique features which better meet individual consumer needs and for which consumers have a stronger willingness to pay (Piller et al., 2004). At the same time, for consumers the promise of buying custom-tailored solutions is the enhancement of their perceived value through receiving superior feasible compositions which differentiate them from their peers (Schreier, 2006).

The general idea of pursuing the competitive strategy of offering higher variety by diversifying portfolios is not new to academia. Already in the early 1980's differentiation was established within marketing and business domains as one of the major generic strategies for companies (Porter, 1985). The basic marketing logic behind differentiation is to employ a broader range of product choices, in order to better satisfy the needs of customers. Instead of only competing on prices as in mass markets, this additional value creation should allow organizations to offset their resulting increase in operating cost. As Lancaster (1990) argues, the level of variety can be related to three aspects; the market competitiveness, the level of scale economies and the difference of customer value across products (Lancaster, 1990). With the advancement of information technology (IT) systems, more recently this trend for diversification was reinforced by the ability of customizing individual aspects on products in a more efficient manner and thus rapidly became an important aspect for today's competitive market (Pine et al., 1993). Apart from offering a wide product variety, it has become increasingly important to react quickly to demand changes with new variants at a shorter time span with rapid delivery. This phenomenon has been observed by several researchers, who conclude that industrial firms are in general experiencing a *customization-responsiveness squeeze*, i.e. the need to react quickly upon customization requests and to ensure high responsiveness for their portfolio (Salvador and Forza, 2004). The degree to which customization is utilized, however, is diverse for each firm and may have multitude reasons, including individual customer preferences, regional market requirements, social values or specific application environments. Each *variant* can thereby be defined as the representation of an instance of a class that exhibits slight differences from a common norm (ElMaraghy et al., 2013). Furthermore, the characteristics of the commercially available product variety created through customization may differ across markets and products with examples on the simplest products with only a small number of choices such as sports shoes (Converse, 2014) to larger and more complicated products exhibiting high variety such as automobiles, marine diesel engines or even buildings (Roy et al., 2003).

## 1.1.2 Challenges and enablers of product customization in engineer-to-order industries

### 1.1.2.1 Economic impact of complexity

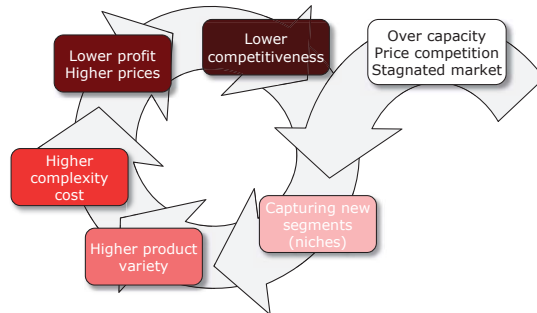
Despite the potential benefits, high and diverse product mixes are not per se beneficial. As studies show, offering more variety through customization may not necessary lead to an increased consumer value and handling this variety may be particularly difficult to realize (Berman, 2002). From a mass production point of view, a major disadvantage of the development towards the smallest niche markets lays in the fact that the production, although much narrower oriented to customer needs, has still been based on sales forecasts. Because customization is still only approximately rather than a de facto fulfilled, operations have to be organized around higher number of variants, in order to correspond to the preferences of niche markets. Accordingly, with the increased planning effort, risks often arise towards excessive inventories or longer lead times. Hence, a trade-off exists when the additional costs of customization can no longer be compensated due a reduced competitive advantage from economies of scale, scope and learning (Pollard et al., 2008). This uncontrolled increase in variety is illustrated in Figure 1-1. As companies are adding more variants, they transform their portfolio from selling few standard products in high volumes, to many low-volume products with many variants. This change in frequency limits the economic advantages to a point where product variants are being introduced, for which the cost exceed the market prices and hence lead to losses. This effect occurs whenever the profit from the additional variants is overestimated. The now higher priced standard products are often subsidized with customized ones (cannibalization), which decreases competitiveness and leads to a competitive disadvantage (ElMaraghy et al., 2013).



**Figure 1-1: The variety challenge of manufacturing**

Source: Adapted from (ElMaraghy et al., 2013)

Operations management literature addressing the challenge of an uncontrolled increase in product variety often vaguely refers to a related increase in operational complexity. Traditional mass producers operating with higher complexity levels as they invest in innovation and further development of their product portfolio are anticipated to experience a drastic decrease in efficiency in sales, design, production and distribution (Åhlström and Westbrook, 1999; Blecker and Abdelkafi, 2006). This negative impact of variety induced complexity has sometimes been described in academia as the vicious cycle of the complexity trap, where external factors force companies to seek new segments, leading to more variety, higher complexity cost, higher prices or reduced profit, which in turn resulting in lower competitiveness (Kaiser, 1995).

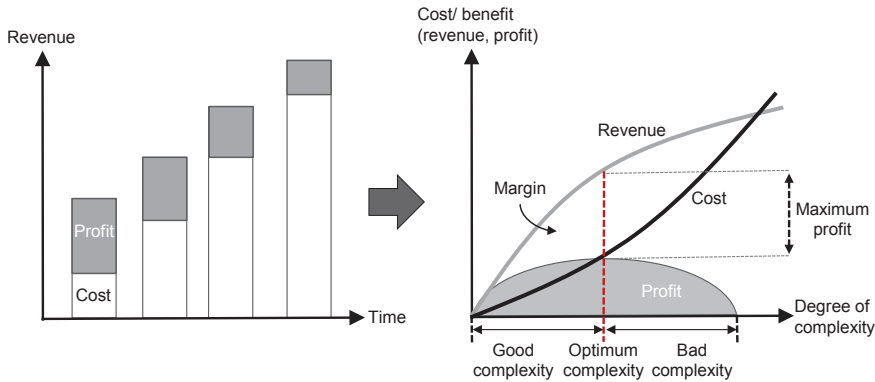


**Figure 1-2: The vicious cycle of the complexity trap**

Source: Adapted from (Kaiser, 1995)

Figure 1-2 illustrates the negative cycle an increase in complexity may lead to. Understanding the value of the complexity cost may reveal strategies for handling this variety induced complexity. Hence, the complexity trap can be overcome, when the product variety is scoped to the optimum range (Lechner et al., 2011). If on the other hand no control mechanisms are applied, an increase in turnover as a consequence of an increased product variety will not necessarily lead to an increase in profit. This interaction between profits and revenue from variety can be generally related to the level of scale economies (Lancaster, 1990). The common argument is that as complexity increases over time, cost rise and profits tend to shrink instead. Figure 1-3 illustrates this effect, where with an increase in product variety

the company misses the economies of scale for the additional variants. Therefore, even if the revenue increases, it can no longer compensate for the additional increase in cost needed to provide these variants. This behaviour is demonstrated in Figure 1-3. Here, profit is represented as a continuous area, which results from the difference between revenue and cost. If the company offers too much variety, it loses economies in scale through its value chain due to “bad complexity”. On the other hand, if too little variety is offered for too small markets, the potential for a scale economy will not be obtained to a sufficient degree, limiting the benefits from “good complexity” (Wilson and Perumal, 2009). Maximum economies of scale can be achieved, when the right balance is found from variety and thus between revenue and cost.

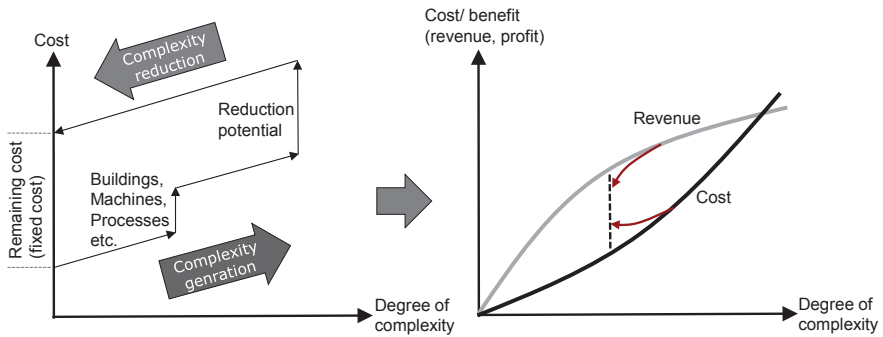


**Figure 1-3: Extension of revenue but not profit due to exceeded optimum in complexity**

Source: Adapted from (Götzfield, 2013, p. 64; Kaiser, 1995, p. 111)

As noticed by some researchers, when dealing with a certain complexity level with the objective to reduce the negative impact of bad complexity, some supplement complexity cost may remain. According to Rathnow (1993), internal complexity rises over proportionally, when additional investments have to be taken, such as new machines or processes, to manufacture the increased product mix. Hence, *internal complexity* is seen as a function of the value chain of enterprises and may relate to sale and marketing, product development, production, logistics etc. (Kaiser, 1995). The additional investment may not be directly revocable when the initially created product variety is reduced afterwards (Rathnow, 1993). This effect is displayed in Figure 1-4 below. Once the optimum level of complexity has been passed, it becomes very difficult to return the initial optimum. The described additional investment for facilities and equipment is often seen as fixed cost, which can in the short to midterm not follow the direct fluctuating demand caused by the *external complexity* (Scheiter et al., 2009). Instead, without reducing any structural aspects of the system, like selling machines or outsourcing processes, the new reachable optimum would result in higher cost and lower revenue.



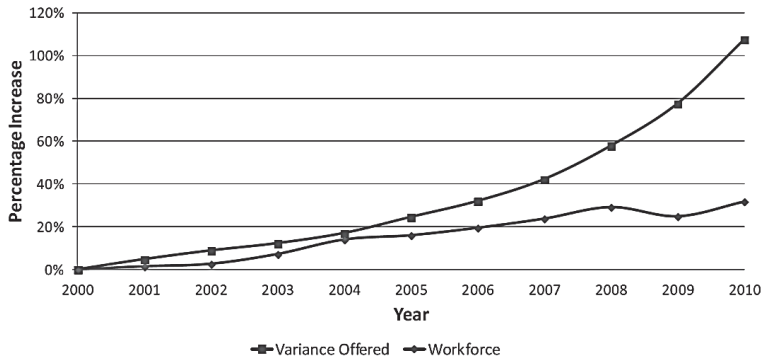


**Figure 1-4: Reducing complexity without omitting all complexity cost**

Source: Adapted from (Kaiser, 1995; Rathnow, 1993)

#### 1.1.2.2 The impact of complexity in ETO companies

Even though less studied, the phenomena of increasing complexity leading to an increase in variety is particularly evident on the example of engineer-to-order (ETO) companies, which core business is to create bespoke product variants that are engineered to the specific requirements of a customer (Wikner and Rudberg, 2005). Unlike mass production firms that push their variants to a market, such ETO variants are generally created through a pull principle, reflecting a particular customer requirement. A recent study with a leading provider of custom tailored two-stroke diesel engines within the shipbuilding industry exemplifies the challenges with growing variety. An investigation of orders shows that over the years even such complex and traditionally highly individual products have been offered with an exponentially growing amount of variety.



**Figure 1-5: Percentage development in variants offered & workforce**

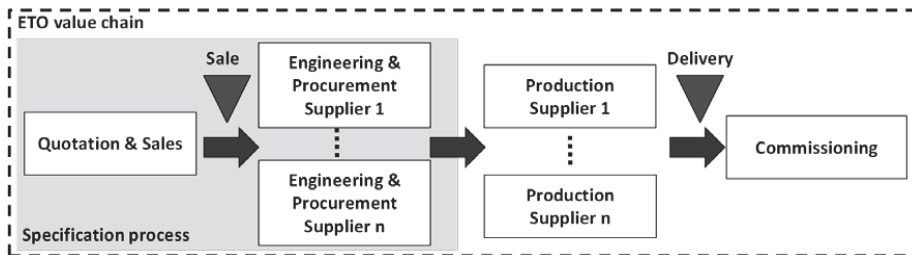
Source: Adapted from (Ulrikkeholm, 2014, p. 15)

As displayed in Figure 1-5, while the number of different variants has more than doubled over the last ten years, the work force has not nearly been expended to the same amount. Assuming that the yearly labour productivity is improving at an average rate of 2-3% (Gust and Marquez, 2004), this trend cannot be simply explained by the advancement of IT technologies, such as computer aided design (CAD) systems (Demeter et al., 2011). Instead, based on additional in depth analysis complemented with several performance measures, the author argues that for the case company this diverse divergence has resulted in both reduced on time delivery and poorer product quality, potentially leading to reduced margins. However, rather than controlling or reducing the overall product variety, like many other globally operating ETO firms, the case company has decided to strive for keeping its

market share through their progressive diversification strategy, while improving its operational performance when customizing products. In doing so, the firm believes that when offering such unique solutions to potential customers it can stay ahead of competition. Though at the time of the study it was still unclear how these performance improvements can be obtained permanently. The prevailing idea was that the commercial variety can be obtained, by establishing a clear picture of where complexity occurs internally and thereby somewhat reducing it (Ulrikkeholm, 2014).

The described example within the diesel engine industry is not unique for ETO companies, but results from a number of differences compared to enterprises engaged with mass production. The obvious difference refers to the nature of products as such with respect to manufacturing control, product lifecycle and complexity etc. (Rahim and Baksh, 2003). Besides, a common characteristic for ETO operations is that the product is reengineered after an order has been placed and before production can start (Caron and Fiore, 1995). This relation can be explained schematically based on a high-level representation of the ETO value chain in Figure 1-6. In a general scenario, more than one company ( $n > 1, \forall n \in \mathbb{N}$ ) may be involved in mutually contributing to the engineering and production of a product (Gosling and Naim, 2009). The *specifications* which constitute all relevant product information for production and delivery are created in the so called *specification process* (Hvam et al., 2004). This process includes the creation of specifications coming from the quotation phase as well as the definition of detailed ones during the engineering phase.

The specification process may involve aspects for both standard and customized products. As ETO firms are mainly concerned with providing bespoke products that require a certain amount of engineering, at the point of sale they typically have only a limited amount of information available concerning their product specifications. Yet, legally binding quotations have to be created upfront, which ensure to their customers the correctness of prices, promised lead times and design feasibility (Rahim and Baksh, 2003). Hence, ETO firms need to be able to create legally binding sales quotations, which define the product to a considerable level of detail, ensuring that the communicated design, price and lead time results in a satisfying profit. A major challenge in an ETO environment therefore is to balance customer requirements with both technical feasibility and production capability for each potential order, thereby ensuring profitability.



**Figure 1-6: Basic engineer-to-order value chain**

Traditionally, the uncertainty of dealing with insufficient information during the quotation phase is addressed through a tight and cycling collaboration between marketing, engineering and production planning before quotations are submitted to customers. This great amount of coordination effort during the specification process already increases the time to market, i.e. the time it takes to provide an offer to the customer, and obtains a high risk for specification errors (Konijnendijk, 1994). In addition, as the success rate is often less than 30 %, generating quotations per se have shown to be no guarantee for receiving an order (Konijnendijk, 1994; Wu et al., 2012). In consequence, on the one hand quotation processes have to be very cost efficient and effectively deliver accurate descriptions at a minimum amount of time. On the other, the simultaneous increase in product variety makes the man-

agement of the entire ETO value chain more complex and requires a cross disciplinary approach to support decisions for creating specifications related to products and processes (Helo et al., 2013). Few empirical studies have investigated these challenges in more detail and have estimated their individual impact and likelihood for ETO organizations (Gosling et al., 2013). The most important issues and ways they can be addressed in this context are summarized in Table 1-1.

**Table 1-1: Basic challenges and enablers in ETO industries**

Source: Adapted from (Gosling et al., 2013)

Category	No.	Challenge	Cause	Enabler
Product	1	Design changes/ incorrect specification	Late client changes Vague designs Get design to late	Design freeze Early involvement in design
	2	Unable to establish site readiness	No access to up to date drawings and programs	Real time IT systems Proactive communications
	3	Excessive product variation	Designers (architects) do not standardise Project variation	More standardisation Product flexibility
Process or Logistics	4	Poor information exchange	Fragmented supply chain	Real time IT systems Team working initiatives
	5	Integration of related trades	Trades ignorant of each other's requirement	Team working initiatives Early conditioning for customers and trades
	6	Access issues	Poor site management and planning Site constraints	Improved site logistics Delivery flexibility
	7	Payment & chains of custody	Fragmented supply chain	Track and trace IT systems
	8	Competitive tender process	Tender uncertainty	Relationships with customers Collaborative forecasting

The results summarized in Table 1-1 confirm the previous discussion on the customization-responsiveness squeeze. The investigated challenges can either concern the products as such or related business processes, which are necessary for their realization. Product based challenges are mainly addressing the discussed aspect of inaccurate specifications, excessive and uncontrolled increase in product variety and the inability to describe, support and represent the product design. Stronger collaboration, better (i.e. modular, standardized and adjustable) product design and the use of supportive IT systems are seen as basic ways to overcome these issues. Similarly, process and logistics related challenges arise from the lack of information availability, sharing and information processing throughout the value chain. General improvements can be achieved through the use of appropriate IT systems, better planning methods, as well as through closer collaborations across the supply chain.

Even though the listed recommendations may appear to be rather obvious, there is little evidence that major improvements, for example from adopting technological advancement in support of customization, have yet been achieved in practice (Gosling et al., 2013). Instead, as a recent study within construction as another major ETO sector shows, within the last decade the construction costs for supplying bespoke houses have not been reduced considerably, despite the increasing focus on improving and systemizing building processes (Thuesen and Hvam, 2011). Consistent with the overall process related findings provided by Gosling et al. (2013), the authors conclude that a stronger systematic reuse of best practises and working methods is needed to contribute to an efficiency increase of constructing individual buildings. While this insight is arguably relevant for a vast amount of ETO firms, it leaves many of the described customization challenges unconsidered.

### 1.1.3 Mass customization as a way to address the customization-responsiveness squeeze in ETO industries

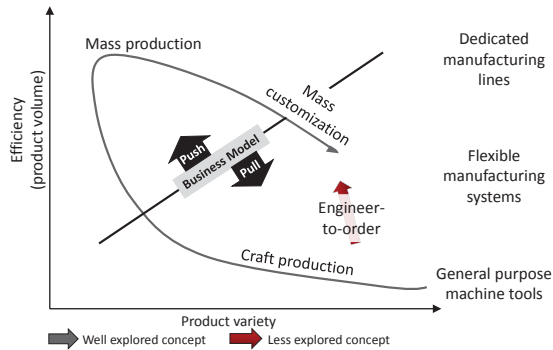
A variety of approaches have been proposed ways to address the discussed customization-responsiveness squeeze, including knowledge-based engineering (KBE), flexible manufacturing, postponement and product modularity (Meredith and Akinc, 2007; Rodriguez and Al-Ashaab, 2005; Rudberg and Wikner, 2004). Researchers working within this area have recognized the need for a consistent framework, which covers the related aspects more thoroughly. Davis (1987) popularized the idea of mass customized products that need to be quickly designed, produced and delivered to meet specific customer needs at prices close to mass produced ones (Davis, 1987; Tu et al., 2001). Jiao and Tseng (1996) express the objective of *mass customization* (MC) more precisely as the delivery of an increasing product variety to satisfy diverse customer needs while maintaining near mass production efficiency (Tseng and Jiao, 1996). This emerging strategy is the response to a massive customer demand for inexpensive and yet individualized products and constitutes an alternative hybrid strategy to Porter's generic forces (Porter, 1985). In particular, it aims at combining the two traditional manufacturing practices of mass production and craft production with the objective to enable customization at high "near mass production" efficiency and stable quality (Duray, 2002; Trentin et al., 2012).

Literature addressing this topic is typically concerned with different implementation methods of MC (Blecker et al., 2004) and predominantly deals with approaches supporting the conversion from mass produced goods to mass customized ones (Pine et al., 1993). To this end, more recently several capabilities have been suggested to enhance the effectiveness of implementing MC (Salvador et al., 2009). Apart from the efficient communication and definition of variants throughout the specification process, the authors discuss suitable production methods and the need for a constant evolvement of the offered variety. Simple mass produced yet customizable examples, such as sports shoes, are used to describe the capabilities in the context of process related challenges, yet disregarding the nature of the actual product design. Other complemented frameworks suggest the application of facilitating modelling methods and dedicated IT systems to increase the effectiveness and efficiency of the specification process (Hvam et al., 2006; Salvador and Forza, 2004).

Hvam et al. (2005) propose a comprehensive approach to the redesign and assistance of specification processes for configurable products with product configuration system (CS) (Hvam et al., 2005). *Configurable products* are considered to have a predefined set of exchangeable components with a predesigned product architecture (Jiao et al., 2000). They are typically provided with an assembly-to-order (ATO) strategy, where postponement is employed to delay the variant creation (Su et al., 2005). Furthermore, the architecture design needs to account for high variety as an essential aspect of the product development process (ElMaraghy et al., 2013; Ulrich, 1995). Comparable to the modelling method of Hvam et al. (2005), a number of additional techniques have been suggested to enhance the creation and management of configurable architectures for ATO products in MC (Du et al., 2001; Jiao et al., 1998).

In contrast, providing ETO products in a mass customized manner has seldom been examined as a possible way to overcome some of the above mentioned challenges with respect to the customization-responsiveness squeeze. Instead, only few sporadic examples exist in literature, where the topic has either been addressed in a very narrow perspective (Brunoe and Nielsen, 2012; Kubiak, 1993; Thuesen et al., 2013), or very general discussions have been performed based on contingent literature studies (Haug et al., 2009). Brunoe and Nielsen (2012) study how the modelling effort of architectures of ETO products can be reduced, by limiting the modelling scope to few elements needed to estimate prices during the sales and quotation process. Kristianato et al. (2012) use a simplified model of an engine consisting of a small number of components, to generate a preferred solution of an architecture with a stochastic programming framework (Kristianto et al., 2012). Thuesen et al. (2013)

investigate how a contractor within the construction industry may increase its efficiency through postponement.



**Figure 1-7: The evolution from craft production to mass customization**  
Source: Adapted from (Kotler, 1989)

Haug et al. (2009) argue based on existing literature that mass producers moving towards MC are in sum challenged to; improve the experience for users when configuring a product, handle the increase in the internal product variety (or complexity), create a valuable commercial variety to the customers and embrace the increase in costs and lead times. Conforming with previous discussions, from an ETO perspective one could conclude that it is necessary to reduce the excessive product variation and to increase efficiency throughout the business processes. The authors conclude that the unbalanced view of MC restricts many practitioners and researchers to investigate the topic more thoroughly, questioning the possibility for ETO firms to become “mass customizers” (Haug et al., 2009). Figure 1-7 illustrates the dilemma of this unbalanced approach towards MC as initially described by Kotler (1989). The author uses the graph to describe the evolution from craft production through mass production to MC, where inter alia improved and flexible production methods have enabled an increase in efficiency and hence in product volume. This research suggests the investigation of the less explored path, which is to enable ETO firms to implement MC with a concept tailored to their circumstances.

#### 1.1.4 Research objective and research questions

As discussed in the previous sections, addressing the customization-responsiveness squeeze is important aspect in today’s competitive environment; its handling can cause severe profit losses, and appropriate management can provide profitable growth. MC offers a promising paradigm to manage the customization-responsiveness squeeze adequately. The capabilities required for a successful implementation of MC need to be understood and further developed from an ETO perspective to address the challenges based on the discussion in Section 1.1.2.2. Consequently, the overall objective of this research can be broadly formulated as follows:

##### **Overall research objective:**

Improve the quality of MC capabilities

This objective is very encompassing and gives possibility for many potential research questions. To narrow down the research, this thesis elaborates the on the present understanding of the MC concepts and implications, identifying the need for a more comprehensive framework with respect to the discussed ETO environment. To lead the course of this research,

several research questions have been developed and accordingly addressed throughout the thesis.

The first research question (RQ) refers to the definition, assessment and development of the MC capabilities as a means to support the transition process towards MC.

**RQ1:** How can the transition process of ETO companies moving towards MC be supported effectively?

There may be many possible ways to support this transition. Therefore, two sub questions have been formulated to obtain a more tangible level. The term *effectively* refers to the need for a guided process, which includes activities that are likely to lead to the desired situation.

**RQ1.1:** What general capabilities should ETO companies develop when implementing MC?

**RQ1.2:** How can the quality of such general MC capabilities be assessed and their development be further directed?

This first sub question *RQ1.1* deals with the definition of the underlying capabilities. The question was initially answered by reviewing key publications on capabilities for MC and discussing on the main subjects. The second sub question *RQ1.2* addresses the assessment and direction for further development of the formulated capabilities. The understanding generated from the literature review was comprehended with empirical investigation. The results were used to refine the obtained insight and to formulate the second research question:

**RQ2:** How should the specification process of ETO companies moving towards MC be developed?

This question explores the development of a specification process, as an essential part of the ETO value chain. To create a more precise investigation of the question, it was divided into the following sub questions:

**RQ2.1:** How can postponing the customer order decoupling point be enabled and how does it affect the specification process of ETO companies?

**RQ2.2:** What are expected benefits, risks and limitations when implementing CSs for ETO products?

**RQ2.3:** How should CSs be used to assist the specification process in ETO companies?

The gained insight in *RQ1* determined the formulation of this sub questions. *RQ2.1* evaluates the characteristics of postponement and its impact on the specification process. This was achieved by reviewing relevant literature combined with an empirical investigation. *RQ2.2* investigates the expected benefits, risks and limitations from implementing CSs in support of the specification process. To answer the question, a systematic review of key publications discussing the topic in general was performed and put into the context of the research. The generated understanding created the basis for the subsequent question *RQ2.3*. This last sub question deals with the purposeful implementation of the IT systems with the objective to create a desired situation.

Based on the understanding the importance of architectures from *RQ1*, a third research question was developed.

**RQ3:** How should architectures for mass customizing ETO products be designed and managed?

Literature discusses architectures from various perspective. Therefore, more concrete sub questions addressing this topic were stated:

- RQ3.1:** How can architectures user for mass customizing ETO products be described explicitly and visibly?
- RQ3.2:** What is suitable architecture design strategy for mass customizing ETO products?
- RQ3.3:** How can a consistent architecture design process for MC be organized?
- RQ3.4:** What are preferred architectures for MC and how can they be formally described?
- RQ3.5:** How can the complexity of ETO architectures in MC be assessed and managed?

The questions are formulated after the insight from the previous questions was available. The answer to *RQ3.1* addresses the need for an explicit (i.e. complete and correct) and visible (graphical) representation of architectures. The question is answers based on an extensive literature review, which set the requirements for several empirical studies. Due to the limited insight available in literature, *RQ3.2* was answered through an survey with relevant companies operating with architectures for MC. The answer to the question determined the direction for answering *RQ3.3*. To obtain an application to practice and evaluation of the created method, a detailed literature study was used in combination with empirical investigations. Finally, the same strategy was applied to answer *RQ3.4* and *RQ3.5*, where in addition several executable tools were developed. *RQ3.4* and *RQ3.5* deal with the challenge of complexity and how adequate assessment and management of architectures can be used to reflect upon the level of complexity in ETO companies.

## 1.2 Research scope

To be able to address these aspects, the following section characterizes the scope of the thesis by first establishing a common understanding of the related concepts and consequently delimiting the research area.

### 1.2.1 Terms and definitions

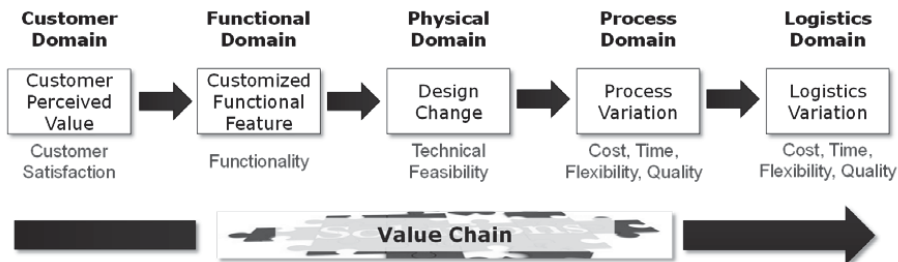
#### 1.2.1.1 Domains in product customization

According to Jiao et al. (2007), when customizing products the entire product realization process, also referred to the value chain, is affected. As illustrated in Figure 1-8, such a process can for example be described based on Suh's domain framework (Suh, 1998). From the customer domain, customer satisfaction is achieved by a given customer perceived value. This value can be expressed by the attributes of a product, such as color or performance. A particular customer value can then be realized by customized functional features in the functional domain, which in turn generate a design change in the physical domain and a variation of processes in the process and logistics domain. The objective for the functional domain is to achieve customer satisfaction through a well matching functionality of the product. In the physical domain, technically feasible design solutions are fulfilling the functionality requirements of the requested customization. Eventually, the customized design is realized under the time and cost restrictions of the process and logistics domain (Jiao, Simpson, et al., 2007). Besides the described objectives for each domain, it can be argued that high quality and flexibility should likewise be pursued for efficiently fulfilling the re-



requested customization within the process and logistics domain. After all, flexible and reliable processes that quickly adapt to a given customization order are crucial for the operational performance of mass customizers (Duray, 2006). In avoiding the trade-off between efficiency and flexibility, companies are utilising platform concepts to balance the required level of standardisation, while maintaining the desired flexibility throughout the value chain (Jiao, Simpson, et al., 2007).

For the purpose of this thesis, the main focus of the research is on the impact from mass customizing ETO products on the different domains of a company, as proposed by Suh (1998), thereby confining other supplementary areas such as supply chain coordination (Chandra and Kamrani, 2005). Furthermore, to avoid the risk of misunderstandings from using unclear definitions (Piller et al., 2004), aspects discussed in the following sections are and set in relation to this general framework.



**Figure 1-8: The different domains of customization throughout the value chain**

Source: Adapter from (Jiao, Simpson, et al., 2007)

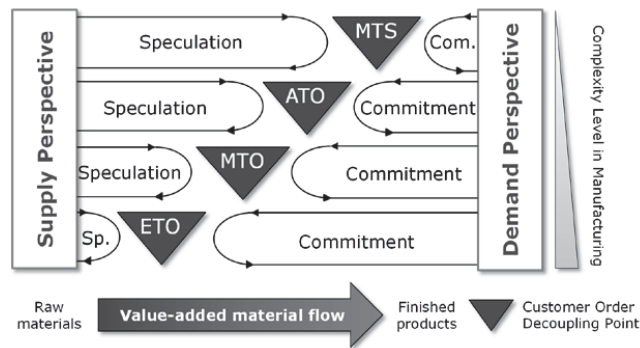
#### 1.2.1.2 Manufacturing control and postponement

A common way to describe how customization is being organized within a manufacturing company is to relate it to the way the manufacturing control of material is realized. When comparing the two extreme cases of production systems, i.e. make-to-stock (MTS) and ETO, several major differences can be seen. One main characteristic relates to the *customer order decoupling point* (CODP), i.e. the point where the in the manufacturing process a product is committed to a specific customer order (Wiendahl and Scholtissek, 1994). Figure 1-9 illustrates the placement of the customer order decoupling point relative to the most commonly used manufacturing control setups, i.e. ETO, make-to-order (MTO), assemble-to-order (ATO), and make-to-stock (MTS). Mass producers are usually associated with a MTS production. Their CODP is located very late throughout their value chain in manufacturing, i.e. throughout their value added material flow. In other words, their production activities are mainly based on forecasted demand, which the manufacturer has speculated about during the planning horizon. In this way, production can exploit high volumes to achieve economies of scale, but is typically limiting the possibility for variety (Jacobs and Swink, 2011b). For ETO manufacturers on the other hand, the CODP is positioned at an early stage of value added material flow. They often deal with one of a kind products with unique designs and sequence of operations (Rudberg and Wikner, 2004).

Another distinguishing aspect of the discussed production systems refers to the development of a *solution space* for a particular product family. The solution space, or sometimes described as product space (Forza and Salvador, 2008), can be defined as the combined variety of the customization domains to form a desired commercial variety. In a MTS strategy products are pushed directly to a target market, which typically restricts the development of a solution space to a predefined and relatively narrow area. Due to the increased customization demand, this area has to be gradually extended (see Section 1.1.1). On the other hand, ETO products are considered to be engineered, i.e. individually customized, without



any predefined limitations with regard to their solution space (Brunoe and Nielsen, 2012). While this distinction may in theory help to illustrate the two contrasting approaches of MTS and ETO, in reality it is however not strictly applicable. Any product available on the market today, regardless if it is ETO or MTS, is constraint by a combination of industry standards, safety and environmental regulations, or manufacturing and engineering feasibility (Konijnendijk, 1994). This thesis therefore suggest a relative size definition of the solution space in which MTS companies operate with relatively narrow and ETO companies with relatively large solution space. Therefore, as indicated in Figure 1-9, the early commitment to a particular order combined with an relatively large solution space makes the complexity level in ETO manufacturing relatively high with respect to the other manufacturing control setups (Wiendahl and Scholtissek, 1994). To achieve MC, companies coming from a MTS strategy need to move towards an ATO production (Yang and Burns, 2003). On the other hand, ETO companies need to accept a higher level of product and/or process standardisation, while postponing the COPD further down the value chain to a MTO or ATO strategy (Haug et al., 2009).



**Figure 1-9: Classification of different manufacturing control with respect to the customer order decoupling point**

Source: Adapted from (Wiendahl and Scholtissek, 1994)


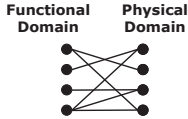
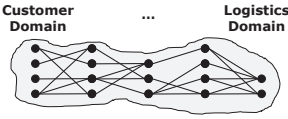
### 1.2.1.3 Classification of products and processes

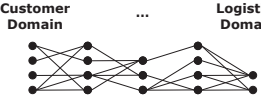
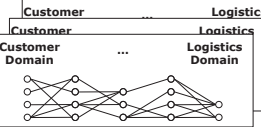
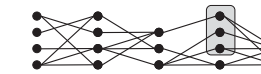
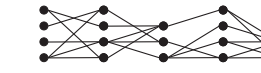
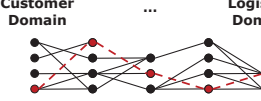
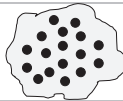
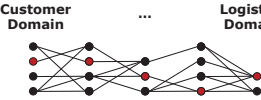

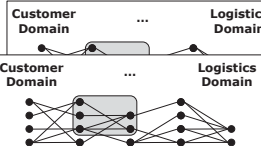
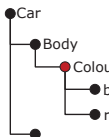
As discussed in Section 1.1.2, constant development of products and product variants can be key opportunity but also risk for the competitiveness of many engineering intensive firms today (Cunningham and Kwakkel, 2011). More variety requires an increased handling effort, since tasks are progressively distributed, environment is rapidly changing and products are becoming more technologically complex. Especially in globally operating firms, the majority of tasks may be performed by teams, who frequently work geographically and temporarily independent from each other (Rodriguez and Al-Ashaab, 2005). In result, in both product development projects and the subsequent customization there is a growing communication concern to be handled (Eckert et al., 2004). An important implication of organizing such collaborative work is to be able to answer the question how a design change will affect the system, either organizational, product or process related (Tang et al., 2010). Traditionally knowledge about partial design solutions relied on the implicit knowledge and experience of individual design engineers (Lee et al., 2001). To keep up with the competitive environment, it has become important to make relevant knowledge explicit in form of representative models and architecture (Erens and Verhulst, 1997), thus available and shareable to all the parties involved in the development process. Companies, which are able to integrate closely the various perspectives of the technical product understanding together with the required knowledge management will succeed in creating better products in shorter lead times. Product knowledge should represent the product features, their relation

to the product components and the way how the created solution meets the marketing strategy. Process knowledge is about the involved business processes, the responsibilities and their interfaces towards supportive technologies. Eventually, project knowledge specifies the resources available, the functional and non-functional requirements, budgets, targets, milestones, and the like (Ebert and Man, 2008). The implementation of adequate IT systems, such as product life cycle management (PLM) systems, hereby facilitates the efficient exchange and sharing of relevant knowledge (Vezzetti et al., 2011).

As knowledge management research demonstrates, companies operating in knowledge intensive domains where engineering and customization are an important aspect of competitiveness, strive for an explicit and efficient representation and processing of relevant knowledge. Due to its importance, literature related operations management and engineering design domains provides a profound definition of the manufacturing related concepts. Important contributions are inter alia provided by (Browning, 2013; Erens, 1996; Felfernig et al., 2000; Meyer and Lehnerd, 1997; Ulrich, 1995). More universal terms are closely described according to dictionary definitions. This Section provides an overview of the terminology used in this thesis to establish a common understanding of the terms and to put them into context with the subsequent content of the thesis.

**Table 1-2: Classification of products and processes**

Product	Any article or substance that is manufactured or refined for sale (Oxford University Press, 2015). Even though services may just as well represent a type of product, in this thesis, a product mainly refers to a physical article.	
Product architecture	(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; and (3) the specifications of the interfaces among interacting physical components (Ulrich, 1995). Erens (1996) complements that product architectures partition the solution space of design, they set conditions for a further decomposition of modules and specify the application or functionality of these modules in a bigger whole.	
Solution space	The term is not directly defined in literature, but is often regarded as the possible variety related to a product design (Forza and Salvador, 2008). From a mathematical perspective, solution space can be seen as a synonym for solution set, which describes the set of all the solutions of an equation or condition (Oxford University Press, 2015). Here, this condition is determined by the underlying architecture. Hence, the term can be defined as the combined variety of a system used to form a desired commercial variety.	

Product family	A product concept of variants designed for a market, which account for different customer needs out of a developed architecture (Erens, 1996). The architecture of an entire family covers the relevant customization domains.	
Product portfolio	A complete set of possible product configurations, i.e. solution space, offered by a business unit (e.g. company) at a given point in time (Meyer and Lehnerd, 1997).	
Module	A cluster of similarly dependent elements with a strong connection within the cluster and weak connections to other clusters (Sosa et al., 2007). Modularity can be used at different hierarchies, such as on product, system or component level.	
Structure	Abstract representation of the underlying elements identified by their type and relations (Andreasen et al., 1995).	
Product variant	A feasible solution of a product family, sometimes also described as a product of its own (Erens, 1996). Formally defined as the representation of an instance of a class that exhibits slight differences from a common norm (ElMaraghy et al., 2013).	
Commercial variety	The totality of product variants derived from a product family.	
Kind	An alternative solution or variant of an object, which constitutes a change in attributes or attribute values (Peak et al., 2004).	
Single product	An independent product with no pre-defined relationships with other products (Erens, 1996).	
Product platform	A set of modules and components and interfaces that form a common structure used to efficiently develop and produce a stream of derivative product families (Meyer and Lehnerd, 1997).	
Attribute	A generic property, parameter or feature used to reason about an object (Felfernig et al., 2000). Attributes may be specific, with a fixed set of values (e.g. colours) or describe a range or values (e.g. dimension).	

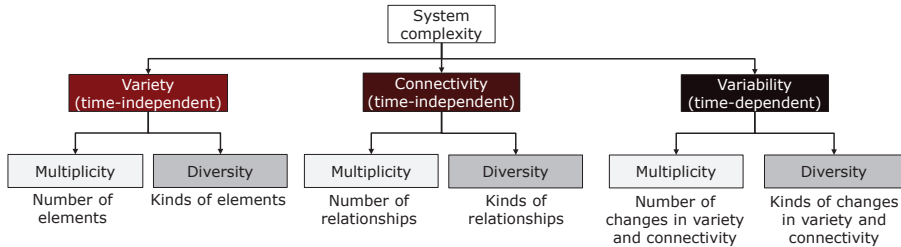
Value	A number in form of an integer or float used to describe a specific state of an attribute (Felfernig et al., 2000).	
Object or class	An element of structure containing one or more attributes (Peak et al., 2004).	
Constraint	Equation describing a relationship of attributes and attribute values. Constraints are often used to exclude unwanted or impossible configurations by prohibiting the selection of certain combinations of primitive variants (Eracar and Kokar, 2012; Erens, 1996).	
Interface	A relationship between elements based a spatial, energy, information or material connection (Pimmler and Eppinger, 1994).	
System	An assembly of elements related in an organized whole. The characteristics of system are expressed through the architecture, i.e. the nature of the elements, their number and the connections between them (Flood and Carson, 1993). A system can partly or entirely cover the value chain of companies.	
Process	A series of actions or steps taken in order to achieve a particular end (Oxford University Press, 2015).	
Business process	Any process undertaken within a system (e.g. department, company or supply chain) contributing to achieve a particular result (Gunasekaran and Nathb, 1997).	
Model	A simplified description of a system to assist an understanding or prediction of a phenomena (Haug and Hvam, 2007; Oxford University Press, 2015).	

#### 1.2.1.4 System complexity

Handling the in Section 1.1.2.1 discussed challenge of complexity has gained increasing academic and managerial interest. Due to its general scope and universal relevance, the topic has led to several inconsistent definitions of the term and therefore often to conflicting frameworks (Geraldi et al., 2011). For many business and marketing related research, complexity is simply a function of variety (Byrne, 2007), where the reason for variety may be related to the number of parts and the number of related kinds (Patzak, 1982). Ways to reduce such variety induced complexity essentially deals with reducing the stock keeping units (SKUs) in an organization. This is often done by categorizing the need for any SKU according to the Pareto or ABC principle (Brynjolfsson et al., 2011). A more comprehensive

approach is taken in the context of complexity in organizational structures (Child et al., 1991) and the handling of complexity in corporate networks (Azadegan and Dooley, 2011). Aside from the variety perspective, complexity of the thereby used systems may consider aspects of connectivity and variability, i.e. how connected the elements of a system are and how strong their number and connectivity varies (Patzak, 1982; Ulrich and Probst, 1988). According to Simon (1962), a *complex system* is made up out of many elements that interact in a non-simple way (Simon, 1962). Related complexity management approaches employ systems theory as a foundation to understand the resulting complexity (Boulding, 1956). Depending on the manifestation of these three characteristics, *systems* can in general be categorized on a continuum between simple, complicated and complex.

Simple systems have a low number of elements, with little connection to each other and low fluctuation over time. Complicated systems are systems which obtain a high number of variety and connectivity and a low number of variability. Consequently, the combination of high variety, high connectivity and high variability is regarded as complex (H. . Ulrich & Probst, p. 58, 1988). An example of complex systems can be seen based on the electronic market. Consider the commercial introduction of smart phone technology. The immediate change in customer behaviour caused organizations to react quickly with a change in their product portfolio, manufacturing processes, suppliers etc. In result, unwanted variety will need be reduced drastically and new variety has to be introducing quickly. Companies that managed to adapt quickly to this variability in demand can be regarded as being more resilient, or robust to the dynamics of markets (Duit et al., 2010). Figure 1-10 below provides and overview of the different aspects of complexity in systems, where according to the discussion above, variety, connectivity and variability are characterized by their multiplicity ("how many") and diversity ("how many different"). According to Simon (1962), the behaviour of such as complex system can only be seen as a whole. This whole is more than just the sum of the individual elements and their characteristics and can only be studied in its completeness through the architecture (see Section 3.5) (Simon, 1962).

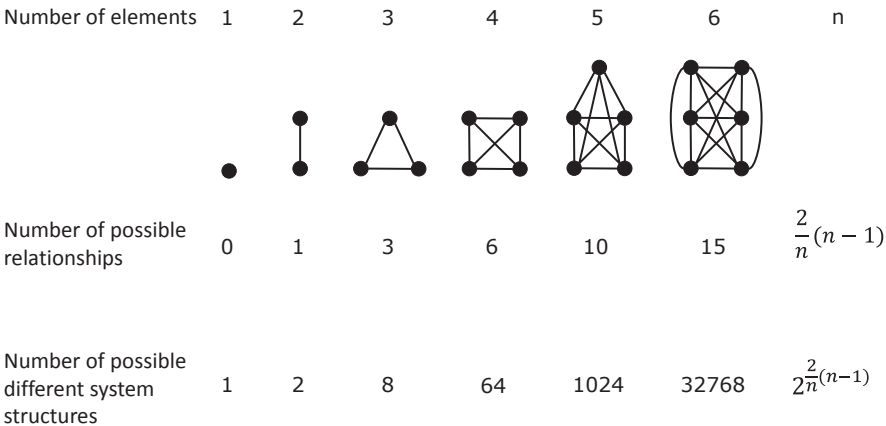


**Figure 1-10: Classification of system complexity**

In the context of engineering, this notion of system complexity has only sporadically been examined. The most profound contribution of a complexity theory in engineering design is arguably presented by Suh (1999). Consistent with the foregoing discussion, the author argues that the complexity of a system has a time-dependent and time-independent. As illustrated in Figure 1-10, the time-independent factor is influenced by the real ("designers do completely understand the system they know") and imaginary ("designers don't know the entire system") complexity of the system. Due to a high variety and connectivity, there is a high risk that the design range developed by engineers differs from the optimum system range. Whereas, time-dependent complexity occurs due to the variability of the system, as it constantly moves away of the design range (Suh, 2005). This perspective on system complexity can be seen as an analogy to the previously discussed complexity trap in industry (see Section 1.1.2), with the market as the system a company is operating in. The commercial variety is performed throughout the customization domains. Variability represents the dynamic changes of customer attributes on markets. As the optimum system range evolves, time-dependent complexity makes it difficult for companies to recognize and qualify this

progress and hence hinders appropriate reactivity. With his definition of axiomatic design (AD), Suh (1999) presented a way how to become more robust to this changes and how to deal with system complexity during product development of single products (Suh, 1999). The different axioms promote a decoupling of the functional requirements and the physical parts, which is generally understood as the increase of modularity. However, despite the detailed approach, it is less obvious how a growing product variety and diversity can be taken into account, making an extension of the concept necessary.

A more pragmatic and quantitative way of classifying the complexity in systems has initially been introduced by Checkland (1981). According to the author, the complexity of a system can be modelled through its structure, i.e. by classifying its elements and relationships. Figure 1-11 below displays the maximum possible combination of structures in decoupled systems, modelled after (Flood and Carson, 1993). Decoupled systems are systems with no constraints, where any possible combination of the elements is possible. While this illustrative model may serve as a good reference description of complexity, it is unlikely to find real world examples to it. Since any manufacturing company is restricted by design ranges, production systems, number of norms, standards etc., this limits the number of possible structures. Furthermore, limiting the classification of a system to its structure reduces the understanding of the occurring the variability and how it can be dynamically addressed. Moreover, elements within an architecture may represent different types of the customization domain. Apart from their relation to other elements, physical components for example contain of a number of attributes describing their particular behaviour. Recent understanding of architectures is therefore that they include both structural ("what it is") and behavioural ("what it does") aspects of a studied system (Andreassen, 2011). A more elaborate approach to architectures is discussed in Section 3.1.

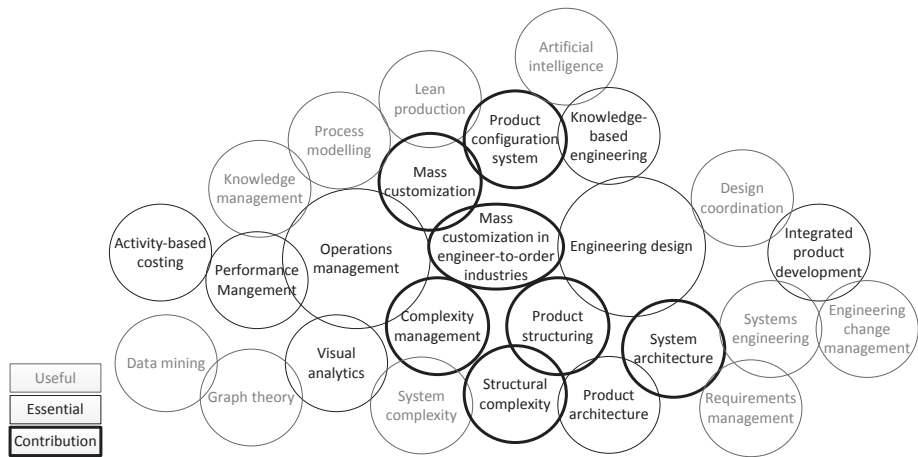


**Figure 1-11: System structures in decoupled systems as a measure of system complexity**  
 Source: Adapted from (Flood and Carson, 1993)

### 1.2.2 Areas of relevance and contribution

The approach introduced in this thesis is a result of a combination of concepts, methods and techniques which originate from a number of different scientific disciplines. The main areas of this research are founded in operations management and engineering design. The main contribution of the thesis relates to the intersection of both areas. Figure 1-12 below provides an overview of the contribution relative to other research areas and the related disciplines. The different size and colour of the disciplines indicate their individual importance

for the thesis. Moreover, the placement of the circles aims at characterizing their relationships to each other, even though their characteristics are not that clearly separable.



**Figure 1-12: Areas of relevance and contribution**

The two main areas ‘Operations management’ and ‘Engineering design’ have a very broad focus and encompass many additional sub-areas, which have not been considered here. For example, a large amount of operations management research concerns supply chain management, services and sustainability, sometimes even in combination. The focus of this thesis relates to the previously defined customization areas, where operations management is seen as a means to describe and qualify the operations, i.e. the business processes at hand. Therefore, the most relevant aspects include ‘Performance management’ and ‘Activity-based costing’ as direct frameworks addressing the assessment of processes. ‘Knowledge management’, ‘Process modelling’ and ‘Lean production’ are seen as assisting disciplines, which are used to enhance the understanding of the research topic. Apart from ‘Mass customization’ as an interdisciplinary topic itself, another important area refers to the use of ‘Product CSs’. Rather than the actual development of the systems, which would refer to the application of programming, algorithms and operations research, this thesis is more concerned with the implementation of product CSs as standard software packages, how they are operated by the users and what impact they have within organizations.

Product CSs are expert systems which originate from the field of ‘Artificial intelligence’ and which are closely related to ‘Knowledge-based engineering’, as a part of supportive systems for ‘Engineering design’. Likewise, ‘Product structuring’ and ‘Product architecture’ are of major concern within ‘Engineering design’. Out of this sub-areas the emerging topics of ‘Structural complexity’ and more generally ‘Complexity management’ have been developed. Due to their management impact, they are linked to ‘Operations management’ and to some extent originate from the area of ‘System complexity’. On the other hand, methods used for describing ‘System architectures’ and evaluating ‘System complexity’ arise from ‘Graph theory’. They make use of ‘Data mining’ for the consolidation of large amount of architectural data and employ with an increasing popularity ‘Visual analytics’ to explicitly and intuitively describe and interpret architectures. The interdisciplinary theme of ‘Systems engineering’ provides this general view on systems, integrating the different customization domains. Such a system view has previously been taken by the idea of ‘Integrated product development’, where ‘Requirements management’ and ‘Engineering change management’ are used to describe the effect of changing product requirements on manufacturing companies. ‘Design coordination’ refers to the organizational aspect of ‘Engineering design’, and how collaborative design work is distributed and handled. It is worth noting that the way how the thematic areas are chosen and mapped relative to each other is rather subjective, since



some of the circles may just as well be connected to other than the hereby described. For instance, 'Graph theory' has been often applied to describe architectures through their structures as further discussed in Section 4.4.

### 1.2.3 Delimitation of the research

Despite the relatively broad scope of research, the thesis is a result of a predefined project, with definite time and resource constraints. This implies that several limitations have to be made:

- The empirical investigation is predominantly performed in manufacturing companies with a strong engineering focus, disregarding other areas, such as finance, pure logistics and insurance.
- The organizational structure of companies and the related social behaviour and responsibilities of employees is not considered, due their fuzzy possibility for interpretation and effective contribution with respect to the achievement of a particular level of operational performance.
- The business processes investigated in the thesis refer to the value chain considered according to the customization domains. Broader supply chain relationships between different companies or multi-echelon systems are beyond the scope of this thesis.
- Marketing aspects, such as market share, promotions, customer preferences or different price strategies are considered only with respect to the definition of value proposition for product families based on customer attributes.
- Methodologies for engineering change management are not considered thoroughly, as related methods are targeting specifically the support of product development, rather than supporting operational customization.
- The evaluation of IT tools only refers to the development and management of product family architectures for MC.
- CSs technologies and related support systems for KBE are not particularly categorized, as this topic would extend the research scope to an insufficient degree.
- Descriptions of detailed programming methods, algorithms or system integrations as a part of any discussed IT development are seen as domains of software engineering and are hence beyond the scope of this thesis.
- The architecture of production systems and any life-cycle processes are modelled with methods appropriate for their analysis with respect to structure, temporal evolution, sequence, and operational performance.
- The empirical investigation is performed with industry partners located in Europe, which depending on the nature of their products partly operate globally.

## 1.3 Research methodology

### 1.3.1 Positioning within philosophy of science

Many of the industry partners examined for throughout this research project are successfully operating ETO companies, which possess a long historical track on their market. It may therefore be assumed that existing best practices have been well adapted, new technologies are quickly implemented and similar processes would result in similar measurable results. However, consistent with the discussion in Section 1.1, evidence on similar companies shows that established techniques, such as the use of CSs in support of specification processes, have not if at all been explored equally. This indicates that reality is not totally independent of the individual as a fundamental assumption of the positivist paradigm (Croom, 2009). On the other extreme, a constructivist approach would mean that an achieved operational performance, e.g. cost of a product, is a relative result of the combined achievement of individuals within a company and cannot be used as an objective comparison measure,



which is not practical for the research problem at hand either. The perused research approach therefore considers postpositivism as more appropriate form.

Compared to pure positivism, which seeks verification of a theory based on a observed phenomenon, postpositivism recognizes that absolute truth cannot be achieved when studying behaviour and actions where humans are involved. Therefore, rather than being totally independent from a studied phenomenon, the researcher himself causes to some extent an influence of an outcome. The developed knowledge is performed in a predominately deductive manner. It starts with an initial theory, where data is collected based on observations and measurements of the objective reality. As the obtained knowledge is conjectural, the theory is then revised and additionally tested through e.g. empirical studies (Creswell, 2013). From this point of view, the objective of science is to evolve the theories to better represent knowledge of reality. This is often achieved by quantitative methods used in combination with qualitative measures to gather broader information about the measured variables (Rynes and Gephart, 2004). The employment of mixed methods combined with a continuous evolvement of the developed theory enables a more valid establishment of knowledge. By doing so, it is hoped that the research results in a better insight into the practices and procedures which are common for studied context. It is thereby appropriate to achieve a level of involvement which is necessary for developing applicable methods, but which at the same time allows evaluating activities from an external perspective.

### 1.3.2 Research approach

A methodology in general describes a system of methods used in a particular area of study (Oxford University Press, 2015). A scientific work further distinguishes between research methodology, which refers to *“a general approach studying research topics”*, and research method, describing a *“specific research technique”* (Silverman, 2006, p.13). In contrast to design research, research within operations management is less concerned with the a particular methodology in form of a general framework, but rather emphasises the proper use of research methods (Croom, 2009). For example, surveys or extensive literature studies are considered to be better suited to answer ‘what’ questions, i.e. the existence of a particular relationship between two elements. Whereas ‘why’ and ‘how’ questions require a deeper context specific information, for which case studies are more assistant. Considering both the limited theoretical understanding of the research area at hand, and its close relation to design research, a suitable research methodology needs to be applied and explorative, to support addressing the research questions to a sufficient degree (Blessing and Chakrabarti, 2009; McCutcheon and Meredith, 1993).

Research within the context of design science often starts a practical problem, which can be addressed by extending existing theory in a systematic way (Popper, 1979). A commonly used methodology within design theory is presented in Figure 1-13 below. Blessing and Chakbarati (2009) proposed this so called design research methodology (DRM) to support researchers within this relatively young discipline with a structured guidance throughout their research project. The framework recognizes the development of understanding (e.g. new theory) and the development of support (i.e. practical decision support) as the two main outcomes research in design should fulfil. The development of theory is organized through an iterative research process, in which the findings empirical and theoretical studies are evaluated and the enhanced understanding determines the process of acquiring further results. In this way, the DRM methodology resembles elements of action research, which however requires the researcher to be part of a created change in praxis (Coughlan and Coughlan, 2002), making case studies of purely observatory nature infeasible.

This Ph.D. work makes use of the DRM approach to guide the researcher throughout the project. The framework is adapted to fit the particular context of operations management with respect to the thereby established research methods.

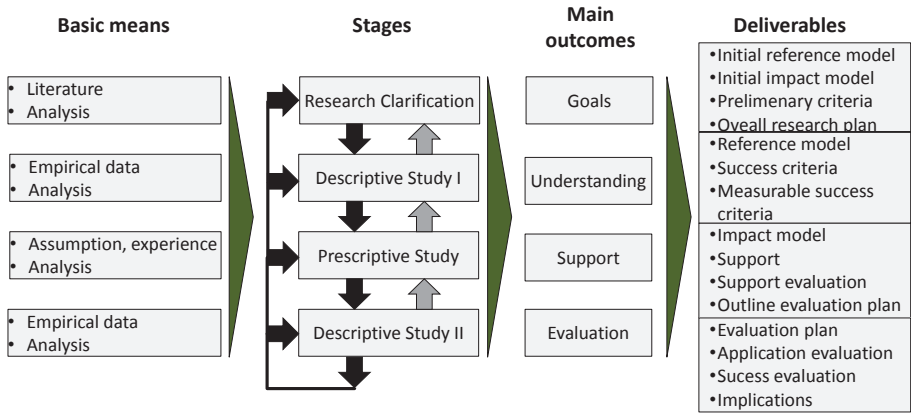


Figure 1-13: The design research methodology (DRM)

As illustrated in Figure 1-13, the DRM framework consists of four main stages. It is deployed to structure the research as an interplay between theoretical and empirical analysis, with the ambition to introduce new methods and tools to improve design. For each stage, basic means are recommended to help the researcher in achieving the main outcomes and deliverables. *Research Clarification* deals with the definition of the research goals with the overall research plan as the main deliverable. Literature review and/or initial empirical studies conducted during the *Descriptive Study I* help to increase the understanding of the research problem.

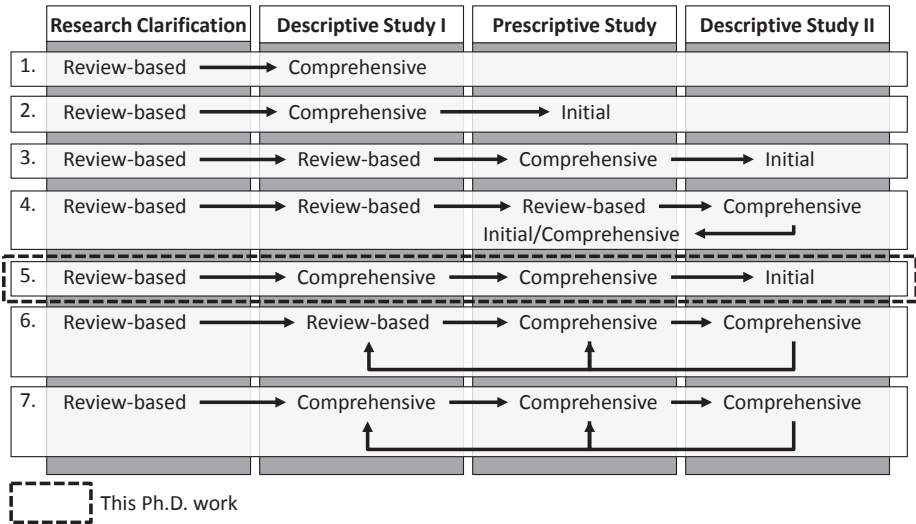


Figure 1-14: Classification of research projects and their focus within DRM

Source: Adapted from (Blessing and Chakrabarti, 2009)

*Prescriptive study* considers the development of improved design support tools as an impact model or the establishment of a theory which describes the enhanced state. *Descriptive Study II* deals with the *Application Evaluation* which assesses how appropriate the support is with respect to the intended situation, and with the *Success Evaluation* which determines the usefulness and implications of the support. The state-of-the-art within a stage and the resources available determine the emphasis of research. For example, if enough results exist

to answer a particular research question, literature review is acceptable, otherwise a comprehensive study, i.e. literature review combined with additional empirical studies, is necessary. The exploratory nature of the research project restricted the possibility for an up-front statement of an impact model. Though a corresponding model was developed in the course of the project and will be presented in its final formulation in Section 1.3.4.

Blessing and Chakbarati (2009) recognise that that it is unlikely that one research project can comprehend all stages to the same degree. Figure 1-14 displays the seven possible categories mentioned by the authors. Due to the limited resources, Ph.D. projects are recommended to focus on the lower categories. As indicated in the figure, this Ph.D. work adapts the fifth category with the following stages:

1. During the *Research Clarification* stage, existing literature was investigated and complimented with insights achieved from discussions with experts (e.g. supervisors and industry partners) from the scientific and industrial network of the author and his immediate research network (e.g. professional and scientific seminars). The results were used to define the research objectives and to develop an overall research project plan (Chapter 1).
2. In the *Descriptive Study I* stage, literature on MC and its application potential within the ETO context was examined (Chapter 2 and 3). Factors influencing the measurable success were further explored. Next, specific aspects relevant for the research questions were searched in literature and comprehended with initial empirical investigations based on a survey and a number of case studies, to obtain a state-of-the-art on the field (Chapter 4).
3. In the *Prescriptive Study*, the results obtained from both the literature and empirical investigation were reviewed and comprised with industrial and scientific experience from the author's group and his network throughout the developed scientific communities (e.g. conferences, workshops and seminars). Moreover, an external research stay in renewed research groups was conducted, to refine the criteria of the impact model.
4. In the *Descriptive Study II*, the concept was gradually evaluated based on further theoretical and empirical investigation from a number of supplementary case studies. *Application evaluation* (support can be used for the intended situation) was achieved through the strong collaboration with other researchers and practitioners. Success evaluation (*usefulness and implications of support*) was considered through the reflection on the obtained results.

Due to the wide-ranging scope of the research objectives and the limited time constraint, the described four stages have not been performed in a strictly sequential manner but to a great extend simultaneously and iteratively throughout the entire research project.

### 1.3.3 Empirical foundation












The empirical foundation employed in this research project is based on several case studies and on a survey (S1) with companies relevant for addressing the particular research question. Moreover, the researcher was to some extent involved in a broader research project. Therefore, the collaborative nature of the research allowed for an investigation on a substantial number of companies across different industries. Table 1-3 provides an overview of the included eleven case studies. A major part of the case studies was conducted within the construction industry, which is of particular interest in the context of ETO firms. However, several complementary case studies were performed outside of the industry, to achieve supplementary insight and triangulation of the developed results. The criteria for choosing the case companies was based on several following factors:

- All companies are manufacturing companies providing products with mainly mechanical nature and varying degree of electronic and software content

- All companies have a strong emphasis on engineer-to-order products as a main part of their portfolio
- All companies are well established on the market and have a traceable interest in research and development
- All companies are globally operating with a main site in Scandinavia
- The challenges of all companies fit with the research objectives
- All companies provide insight into primary data relevant for the research project.

The analyses of sensitive empirical data, such as profitability of product portfolios and architecture models, is usually a key competitive advantage for many manufacturing firms. Therefore, the case studies conducted throughout the research are presented in an anonymous way, to avoid any disclosure of critical insights. Table 1-3 provides an overview over the case studies and their characteristics. The stated duration refers to the time frame within a particular case study was performed and should not be confused with the months. For example, "6 months" indicate that the collaboration with the company lasted six months with respect to the specific investigation.

**Table 1-3: Case study overview**

Product icon	#	Products	Business	Industry	Description	Research focus	Research Question	Duration
	1	Building systems	Professional / Consumer	Construction	Coordinating architecture development for analysis and computer model. Redesigning and assisting detailed design with configuration systems.	- exploring potential for postponement and specification process assistance - redesigning specification process - assisting detailed design	RQ2.1, RQ2.2, RQ2.3	6 months
	2	Building systems	Professional / Consumer	Construction	Initial assessment and development of MC capabilities with a particular focus on redesigning and assisting the specification process	- assessment of operational performance and variability - activity-based costing - redesigning specification process	RQ1.1, RQ1.2	4 months
	3	Building systems	Consumer	Construction	Exploring potential of preferred architectures for mass customization through robust design.	- platform-based design and leverage - product modularization	RQ3.4	18 months
	4	Mechanical / Electrical	Professional	Industrial & Manufacturing Security	Testing and refining performance assessment method for the evaluation and development of MC capabilities.	- assessment of operational performance and variability - activity-based costing - redesigning specification process - modelling production	RQ1.1, RQ1.2	6 months
	5	Mechanical / Electrical	Professional	Oil & Gas	Testing and refining performance assessment method for the evaluation and development of MC capabilities.	- assessment of operational performance and variability - activity-based costing - redesigning specification process - modelling system architectures	RQ1.1, RQ1.2	6 months
	6	Building systems	Consumer	Construction	Extending architecture modelling methods, aligning architecture design, investigating preferred architectures.	- architecture modelling - combining matrix and PVM with fuzzy methods	RQ3.4, RQ3.3, RQ3.4	5 months
	7	Buildings	Consumer	Construction	Exploring postponement and specification process support within new product development and vendor coordination. Investigating architecture development and complexity management.	- architecture modelling - redesigning the specification process - complexity reduction	RQ2.1, RQ2.3, RQ3.3, RQ3.4, RQ3.5	13 months
	8	Building systems	Consumer	Construction	Testing the effect of coordinated product, process and logistics architecture design. Applying postponement and preferred architectures for MC.	- architecture modelling - platform design - redesigning specification process - postponement	RQ2.1, RQ3.1, RQ3.3, RQ3.4, RQ3.5	7 months
	9	Mechanical	Consumer	Furniture/ home accessories	Improving profitability of product variety and quality of architecture through complexity reduction and process architecture improvement	- architecture modelling - complexity reduction - production redesign	RQ3.5	6 months
	10	Mechanical / Electrical	Professional	Process plant & machinery applications	Testing modelling methods, aligning architecture development for analysis and computer model, assisting architecture complexity assessment and management, tool development.	- modelling methods - consistent architecture modelling - architecture complexity assessment and management - architecture quality assessment	RQ3.1, RQ3.3, RQ3.4, RQ3.5	5 months
	11	Mechanical / Electrical	Professional	Process plant & machinery applications	Exploring the scope for redesign and specification process support of complex architectures	- redesigning specification process - assisting conceptual design design - scale and breath of specification systems support - complex architecture modelling	RQ2.3	8 months

The complemented *survey* (S1) was conducted as semi structured interviews within 29 companies. The companies were chosen based on the same criteria as for the more elaborated case studies. Each of the interviews lasted between 30 minutes to one hour and was carried out with employees with knowledge of the particular research field, e.g. product management or configuration project implementation. Apart from the higher response rate, the main reason for using interviews instead of a web based or paper based survey is that the area in focus is characterised by a much unclear terminology. The chosen approach allowed for the interviewer to clarify the meaning of questions that are not understood and to rigorously investigate the nature of the research set-up. This option proved to be particularly helpful because of the different backgrounds of interviewees and the different industrial settings, definitions, and practices of the target organizations (see Section 1.3.1). Furthermore, this research design made it possible to balance the breadth and the depth of the data by allowing for both qualitative explanations and quantitative indications. Further details about the survey and the achieved insights are described in Section 4.4.1.

The obtained results from the empirical investigations were published in several research papers in form of conference and journal articles. Conference articles were in particular used to obtain quick and valuable insight from the related research communities, to enhance the understanding of the topic in accordance with the DRM framework. Figure 1-15 illustrates the contribution of the papers relative to the DRM stages and the stated research questions. The occurrence of the papers within several combinations of research question and DRM stage indicates the strong connectivity and elaborate nature of the research project. Despite the relatively high amount of parallel empirical studies within a board spectrum of research disciplines, each research question was aimed to be addressed sufficiently.

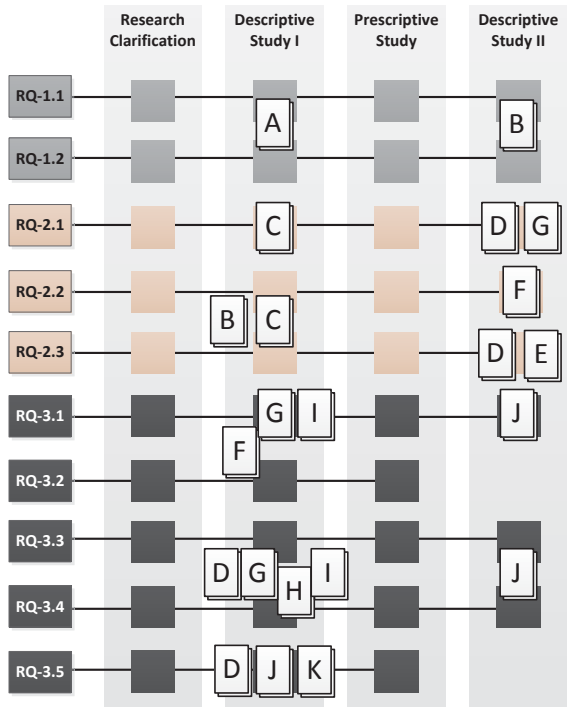
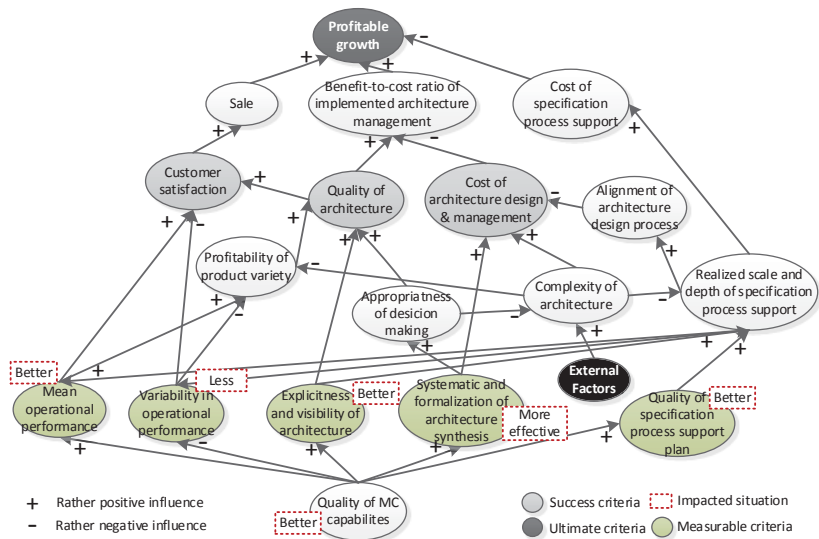


Figure 1-15: DRM stages applied in context of the research

### 1.3.4 Impact model

The impact model representing the construct of this thesis displayed in its final formulation in Figure 1-16. The listed factors within the following be briefly summarized:

1. *Ultimate criteria*: One feasible criteria seen from operations management perspective may be formulated as achieving *profitable growth*. As Section 1.1 discussed, increasing growth without profits may lead to increase in complexity and hence to less profit. Therefore, profitable growth was formulated as a more appropriate objective. However, this criteria is rather broad and abstract, and hence difficult to measure as such without providing any direct connection with some factors possible to be proven (measurable criteria). Additional elements are therefore needed to make the validation of the research more accountable.
2. *Success criteria*: To achieve the ultimate criteria within the scope of the thesis, several success criteria may be formulated. From the context of the thesis, profitable growth may be derived from the *sale* compared to the related cost. An increase in sale however is a long term aspect, which is unfeasible to measure within the scope of the thesis. On the other hand, it is feasible to assume that the amount of sale has a direct positive relationship from *customer satisfaction*. The main cost drivers investigated in this thesis relate to two main factors: (1) to the *benefit-to-cost ratio of the implemented architecture management*, and (2) to the *cost of specification process support*. The former factor (1) deals with the underlying concept of how the architecture is managed. High *quality of architecture* increase this ratio, while the *cost of architecture design and management* reduces it. The latter factor (2) refers how costly the implementation of a CS has been, which in turn is dependent on *realized scale and depth of the specification process support*. Intuitively and later elaborated in Section 4.3, the more IT needs to be developed around the specification system the higher the cost will be.



**Figure 1-16: Network of influencing factors (impact model)**

Source: Adapted from (Blessing and Chakrabarti, 2009)

3. *Measurable criteria*: Since the success criteria are not tangible enough to be measured directly, several additional criteria have been formulated. Operations management literature argues that customer satisfaction can in principle be reduced to operational performance. Higher *mean operational performance* essentially means to

obtain the ability to provide better and cheaper products at lower cost. *Variability in operational performance* on the other hand has a negative impact on the expected operational performance, leading to reduced reliability in quality, cost and lead times. According to literature, operational performance is also directly effecting the *profitability of product variety* (see Section 4.2). According to engineering design literature, the *quality of architecture* cannot be accessed directly, but needs to be derived indirectly from suitable measures. The *explicitness and visibility of architectures* is reported supporting the establishment of good architecture quality. *Systematic and formalization of architecture synthesis* contributes to the *appropriateness of decision making* and may hence lead to higher architecture quality (see Section 3.1). The increase of proper decisions are likely to result in a reduced *complexity of architecture*. Less complex architectures positively influence the profitability of product variants (see Section 1.1), the *cost for architecture design and management* (see Section 3.5.1), and the *realised scale and depth of specification process support* (see Section 4.3). At the same time, the higher the *realised scale and depth of specification process support* is, the larger the coverage of the implemented architecture model, the more likely the *alignment of architecture design process*, the less costly the management of the architecture design will be (see Section 3.1). However, the increased effort for the establishing of a systematic and formalized synthesis may contribute to higher *cost of architecture design and management* (see Section 4.4.5). Finally, the quality of specification process support plan has a direct effect on how capable firms are in increasing the *realised scale and depth of specification process support* (see Section 4.3). This thesis argues, that these four factors are essential for the assessment of how successful MC is performed, i.e. formally described as the *quality of MC capabilities*. The development of the factors towards the desired situation is likely to improve the success and ultimate criteria.

## 1.4 Chapter summary

Chapter 1 provided an introduction to the thesis. First, the motivation of the research was clarified by elaborating the importance, challenges and opportunities of customization for manufacturing firms. This was achieved by discussing how the demand for customization leads to an increase in complexity for both traditional mass producers as well as for ETO firms. Relevant studies were presented demonstrating the negative impact of growing complexity on companies' profitability. Next, MC was introduced as a key concept dealing with the related complexity challenges for mass producers and its application on ETO firms was proposed. Based on that, the research objective was formulated, i.e. to improve the quality of MC capabilities from an ETO perspective. To address this objective, ten research questions grouped into three main subjects were developed. Next, the research scope was set, by describing major terms with respect to the domains of customization, manufacturing control, postponement and by defining the nature of products and processes. Relevant theoretical themes were then stated to display the research contribution and the research delimitation. Finally, the research methodology was formulated by defining the researcher's positioning within philosophy of science and describing the applied research approach. The latter included the adjustment of the DRM as an established framework within design research, followed by a description of the empirical foundation and a formulation of an impact model. The subsequent Chapter 2 elaborates on basic concepts and implications of MC, to establish a common understanding of the subject.



## 2 MASS CUSTOMIZATION CONCEPTS AND IMPLICATIONS

The previous chapter introduced the topic of MC as a way to address key challenges of ETO companies. Specific questions were formulated to narrow the scope of the research project and to enable a stepwise evaluation of the research field. This chapter describes the basic concepts of how mass customized products are obtained. The chapter is organized in three major sections. Section 2.1 elaborates how the possible ranges of customization can be formally described. Next, existing capabilities for implementing MC from a mass production perspective are discussed. Section 2.2 then investigates to what extent the customization of products can be organized with the development of appropriate specification processes, which are supported by CSs. Finally, Section 2.3 provides a summary of the chapter.

### 2.1 Mass customizing products

As discussed in the introduction chapter, the aim of mass customization is to increase the compatibility between customization and responsiveness, i.e. to enable an efficient and effective development, production and delivery of customizable products. While the basic concept can be traced back to the late 1980s (Davis, 1987), a major challenge of this paradigm is to establish the right internal capabilities, which would allow companies to reach a large number of customers as in mass markets with the additional value of tailoring products to specific needs. Apart from adjusting manufacturing processes (Squire et al., 2009), in this context it is important to understand how customization is enabled in general and what additional capabilities are thereby needed for become a “mass customizer”.

#### 2.1.1 Degree of customization and solution space

The schematic representation of the different domains in Figure 2-2 illustrates the degree to which customization may take place at a company. This degree is determined by the solution space, i.e. the totality of all existing variety required to obtain a desired degree of customization. A relatively large solution space indicates that a company allows for higher possibility for customization. The commercial variety offered to markets is a combination of the individual variety from all domains and depends on the interaction between these domains. In its extreme forms, this interaction can take two possible stages. In the most restricted case all relationships are strictly *1 to 1 coupled*, i.e. there is a 1 to 1 connection between the kinds  $k$  across the domains. This would represent an optimum design in axiomatic design terms extended to the entire value chain. Consider a product family, which requires 5 kinds in each domain. The total amount of kinds is then equal to the sum of the five alternatives in each domain, i.e. 25. However, because the kinds are coupled in a 1 to 1 relationship across the domains (i.e. possible number of relationships is 1), the resulting commercial variants remain 5, as only one kind of each of the domains fits to a particular product variant (see Equation 2-1). This scenario resembles the situation, where a product offered in five different commercial variants  $V$ . Each variant relates to a different functional feature, component, process and logistic network. In result, in coupled systems the number of commercial variants is equal to the number of alternative kinds within each domain.

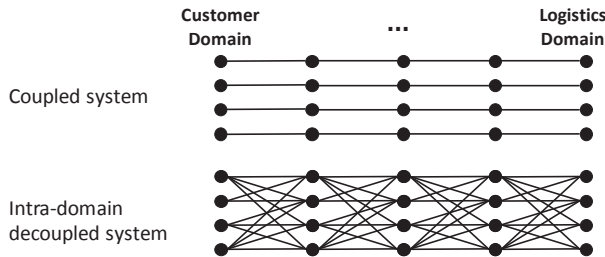
**Equation 2-1: Variety in coupled systems**

$$V(\text{coupled}) = k = 5$$

Similar to a dedicated production line in manufacturing, in this way, this scenario can be seen as a dedicated value chain, with individual parallel lines for each variant. On the other extreme, the five domains can be regarded as being *intra-domain decoupled*. This means their dependency corresponds to the maximum possible relationships between the domains, listed in the sequence of the value chain. In this second scenario the responsible executives of each domain can decide individually about the extent to which they allow for customization, without the need for consulting any of the other domains. Consider the same setup as above of having five kinds  $k$  in each domain. The total amount of kinds remains the sum of all kinds across the domain, i.e. 25. However, the number of commercial variants can now be calculated as the product of the individual kinds  $k$ , which in this example results in a total number of 3125 possible commercial variants (see Equation 2-2). Hence, such a partly decoupled system, the commercial variants grow exponentially with the number of individual alternatives.

**Equation 2-2: Variety in intra-domain decoupled systems**

$$V(\text{intra-domain decoupled}) = \Pi\{k\} = 5^5 = 3125$$



**Figure 2-1: Coupled vs. decoupled customization domains**

The two extreme scenarios are displayed graphically in Figure 2-1. Literature describing such partly decoupled systems typically refers to theoretically derived experiments, which are simplified to fit a developed model (Jiao and Tseng, 2004; Jiao et al., 2000). One of the closest exemplar to a decoupled system may be represented by the traditional LEGO blocks. Their number of commercial variants is determined by the amount of blocks and their kinds in shape, colour and interfaces, each of them independent from each other. These aspects however refer only to the customer, functional and physical domain, which in the best-case scenario are strictly decoupled from each other. The corresponding processes and logistics on the other hand are organized in a coupled manner, to increase efficiency and to gain from economies of scale (Mortensen et al., 2008). This limitation is indicated by the information flow displayed in Figure 2-2. The number of commercial variants is a result of developed solution space. It represents the behaviour of the system (from strictly 1 to 1 coupled to strictly decoupled) and the individual variety of the domains. This behaviour is determined by the architecture of the system and will be discussed in more detail in Section 3.1. It can be therefore concluded that the solution space of any product, regardless if MTS or ETO, can be assigned to an area, which lies between the above described extreme cases.

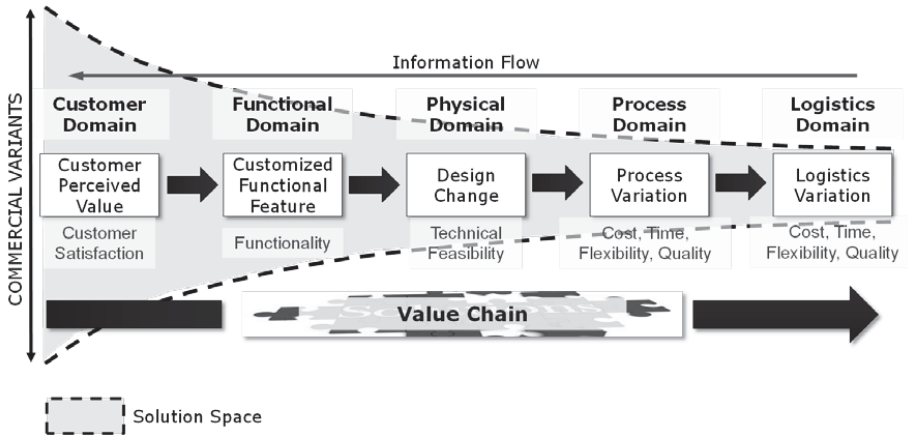


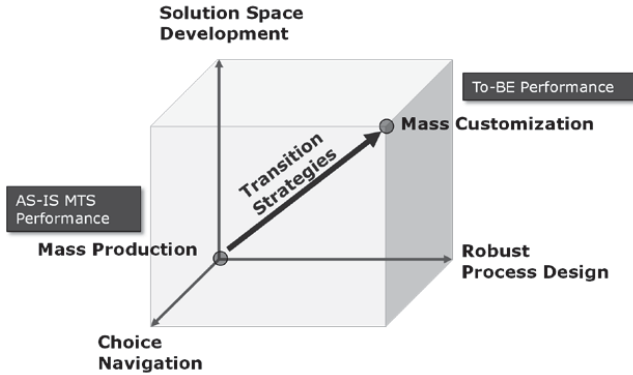
Figure 2-2: Customization domains and solution space

### 2.1.2 Mass customization capabilities for make-to-stock products

Due to its broad application along the value chain of organizations, related literature has been dealing with diverse aspects of the MC concept. While some of the research has investigated business and marketing implications of MC, others have examined its impact on operations, product development, manufacturing and supply chain (Fogliatto et al., 2012). In order to achieve the objectives of the customization domains described in Section 1.2.1.1 more effectively, researchers have proposed several enablers or capabilities MTS companies should establish. Based on an extensive literature review, Fogliatto et al. (2012) for example investigate the use of technology as a major enabler for MC. The authors argue that certain product, process and order elicitation methods combined with information technology (IT) systems considerably enhance the way how customization is fulfilled within organizations. Their investigation shows that in particular the use of product CSs aligned with data mining helps to efficiently identify and translate customer requirements into the functionalities of a product.

CSs can be categorized as subtypes of knowledge-based expert systems, or in short expert systems. They represent the product knowledge relevant to the customer (customer perceived value) in a formal way, allowing a complete definition of possible product outcomes (customized functional features) with a minimum of entities (Hvam et al., 2011). Similarly, from a MTS perspective, Salvador et al. (2009) propose three general capabilities MTS companies should try to develop when pursuing MC: *choice navigation*, *solution space development* and *robust process design*. In general, the term capability refers to the power or ability to perform a certain task (Oxford University Press, 2015). In MC general capabilities should describe a characteristics, which help to determine the quality with which a company is able to mass customize products. According to Salvador et al. (2009), with *choice navigation* a mass customizer should assist customers in identifying their requirements and corresponding solutions (customer attributes) while minimizing the burden of choice. Using software which allows customers to play with the product design and to continuously sensitize their preferences provides clients with a fast cycle of trial and error learning. Another way of achieving a stronger choice navigation capability is through offering products, which while being used dynamically understand the preferences of their users. To create such an embedded configuration companies may not need to customize the actual product components, but rather provide a standard solution which functionality is self-regulating over time. In *solution space development*, a set of functionalities has to be defined which represent best the features requested by a wide range of customers. Various software tools, such as innovation tool kits and virtual concept testing, can be used to facilitate an efficient

adjustment of the offered solution space (Salvador et al., 2009). Eventually, through a *robust process design* existing organizational and value-chain resources, such as flexible automation and adaptive human capital, are reused efficiently under the premise of the process and logistics domain, i.e. under time, cost, quality and flexibility requirements (Neely et al., 2005). Figure 2-3 depicts how the transition towards MC can be developed effectively establishing with the establishment of the described capabilities. According to Salvador et al. (2009) MTS companies working on developing these capacities will be able to obtain a better customization performance.



**Figure 2-3: Transition from mass production to mass customization**

Source: Adapted from (Salvador et al., 2009)

The described capabilities for MTS companies provide a general overview of some of the aspects needed for MC. According to the authors, choice navigation capability should assist the customer in finding the right product in a way which limits the burden of choice. Even though not discussed by the authors, from a customer perspective, CSs have proved to limit this burden by effectively guiding the user to a valid design (Trentin et al., 2013). From a company perspective the systems are employed to efficiently assist the process of choosing a variant, which was formally described as specification process (Hvam et al., 2006). In other words, *choice navigation capability* can be interpreted as adequate assistance of the specification process with CSs. The ways how specification systems are implemented as part of the specification process design is further discussed in Section 2.2. The capability of solution space development then refers to the ability to create a solution space which matches the preferences of customers. As elaborated in Section 2.1.1, the solution space is determined by the architecture and reflects design of the customization domains and their relationships to each other. It is therefore the result of more specific capabilities that enable a desired solution space, indicating the need for a further investigation of the topic. From an ETO perspective, the design of suitable architectures for MC is of particular importance and will consequently be investigated in more detail in Chapter 3. The last capability of robust process design can be related to architecture design, as it covers the entire value-chain for customization.

## 2.2 Specification process design

In simple terms, *specifications* are descriptions, which transfer the needs or intentions of customers into executable requirements. They include any kind of instructions that needed to communicate the achievement of a particular output, i.e. a valid product design. In this way, for customized products a *specification process* can be described as a business process, which lies between the customer needs and the manufacturing of the desired product. The following sections deal with the design and assistance of the specification process, as an

essential part of the customization performance. As this aspect has already been well described in literature, only a brief overview will in the following be provided, considering only the most relevant aspects for this thesis. Further explanation can inter alia be obtained in Hvam et al. (2008) and the thereby recommended references. Moreover, related description is to be found in Forza et al. (2006) with respect to the order acquisition and order fulfilment process.

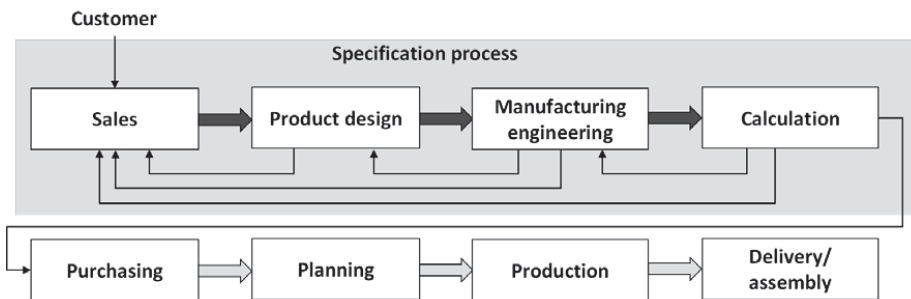
Literature dealing with the development and implementation of CSs suggests a number of ways on carrying out configuration projects in a systematic way. The majority of the studies is thereby focusing on defining the right development and implementation procedure, while only few of them investigate possible strategies for developing product configurators (Haug et al., 2012). Either way, once projects have been initiated, a well-defined framework for developing CSs obviously helps project leaders and domain experts to follow predefined phases, to employ best practices, established tools and suitable modelling techniques. Table 2-1 below provides an overview of a procedure for developing and assisting specification processes with CSs as described by Hvam et al. (2008). The framework is based on established methods for developing a computer model introduced by Booch (1986). The objective of the framework is to handle the complexity of a large software project by breaking down the development work into phases of object-oriented analysis, design, implementation and maintenance (Booch, 1986). Hvam et al. (2008) adapt this framework for developing and implementing CSs as part of redesigning the specification process. By following the lifecycle of a configuration project, the procedure suggests conducting projects in 7 major phases, starting from the planning phase (development of specification processes) first. The authors argue that at the beginning, engineering companies should investigate the way their custom tailored products and services are specified (order fulfilment) and how the communication to the customer (order acquisition) is organized. Analysing the specification process would allow firms to draw conclusions on their current operational performance and to uncover vulnerability.

**Table 2-1: Procedure for developing and assisting specification processes with CSs**  
Source: Adapted from (Lars; Hvam, Mortensen, & Riis, 2008, p. 58)

Phase	Activity
<b>1 Development of specification process</b>	<p><i>Step 1.</i> Identification and characterization of the most important specification processes.</p> <p><i>Step 2.</i> Formulation of aims and requirements for the individual specification processes. Measurement and gap analysis.</p> <p><i>Step 3.</i> Design of new specification process. Definition of the configuration system(s) which are to support the specification process.</p> <p><i>Step 4.</i> Evaluation and selection of scenario.</p> <p><i>Step 5.</i> Plan of action and organization of further work.</p>
<b>2 Analysis of product range</b>	Analysis of product range. Definition of configuration system's overall content and structure. Design of product variant master.
<b>3 Object-oriented modeling</b>	Construction of object-oriented analysis (OOA) model.
<b>4 Object-oriented design</b>	Choice of configuration software. Adaption of OOA model to the chosen configuration software. Elaboration of requirements specification for programming, including user interface, integration with other systems and program dynamics.
<b>5 Programming</b>	Programming and testing
<b>6 Implementation</b>	Implementation of configuration system and the future specification process
<b>7 Maintenance and further development.</b>	Measuring and following up on the new specification process. Maintenance and continual further development of configuration system. Appointment of persons responsible for maintenance and further development.

### 2.2.1 Developing the specification process

As Section 1.1.2 discussed, a well-organized and efficient specification process is fundamental for companies engaged with customization. The first phase of the framework described in Table 2-1 deals with the redesign or as the authors write 'development' of the required specification process. Figure 2-4 below illustrates the activities a specification process may include in a generic value chain of a manufacturing company, as described by Hvam et al. (2008, p. 19). Even though not directly discussed by the authors, the sequence of processes describes the specific case of an ETO manufacturer, in which product design, engineering and production follow after an order has been placed. If alternative manufacturing setups, such as ATO, are implemented, some of the illustrated activities may either be organized prior to sales, e.g. production, or be less significant for the order acquisition and fulfilment, e.g. product design and engineering. The feedback arrows indicate the discussed increase in coordination effort across the different departments. From a supply chain perspective it is moreover important to understand how the communication between various stakeholders is organized and to what extent they are influenced by the specification process. To obtain such an understanding it is useful to create an initial overview over the current specification process at hand, using related modelling methods. A common way to describe involved activities is map them using the Business Process Modelling Notation (BPMN). The BPMN is a de-facto standard for illustrating processes within organizations in a very graphical and intuitive way, thereby providing a solid basis for discussion (Chinosi and Trombetta, 2012).



**Figure 2-4: Generic specification process of manufacturing companies**

**Source:** Adapted from (Hvam et al., 2008, p. 19)

Activities related to the specification process may include the registration of customer requirements to a product, the adjustment of manufacturing drawings, estimation of price and lead times or calculations of technical feasibility. An initial request from a customer typically undergoes several departments, where for each change of responsibility additional information is added. From a customer perspective, many of the activities can be regarded as non-value adding (Hvam et al., 2006). A major objective of mapping the processes is to identify all activities and their created output, such as documents and drawings, needed to describe a product, before it can be produced. With process maps the employees obtain an overview of all related and interconnected activities. Other less commonly used methods for operational process mapping include the IDEF0 standard (Kalpic and Bernus, 2002), or the time-based design structure matrix (DSM) (Pimmler and Eppinger, 1994).

Modelling the specification process with the described methods has been strongly influenced by the preceding and more common description of production processes. The production industry has gone through major improvements in the past decades, where in particular the Lean approach and concept of value and waste have been widely used (Womack et al., 2007). *Value* has often been defined as any contribution or activity which is absolute necessary to provide desired product to the customer and for which the customer is willing



to pay. On the other hand, *waste* is seen as any additional activity which is not providing any direct value (Womack and Jones, 2005). Hence, similar to the Lean methodology in manufacturing, value stream mapping (VSM) may here be applied to separate the non-value adding activities in the specification process from the value adding ones (Braglia et al., 2006). The results can be used for further assessment of the processes, in particular with respect to identifying the highest potential for improvement. Empirical examples and the expected gains of this approach can be found in Hvam et al. (2011). However, today's global competitive environment forces many firms to aim for specification process improvements, which cannot be simply achieved solely by restructuring the established working procedures. In particular for companies whose core business to some extent relies on the efficiency of customization, the implementation of additional technologies is necessary. As already described in Section 2.1.2, in many studies the use of product configurators is regarded as being particularly useful in this respect (Fogliatto et al., 2012).

### 2.2.2 Assessing and redesigning the specification process

According to Hvam et al. (2008), once the current specification activities have been mapped, in the next step, the requirements for the future TO-BE specification process are to be set. The objective of the subsequent phases is to develop a better performing future specification process. However, it is worth mentioning that unlike often stated in literature, the objective of a future specification process is never to make an existing process faster through automation (Haug et al., 2009), but rather to first simplify it radically and to reduce the non-value adding aspects of it (Hammer, 1990). Information technology in particular CSs are then recommended to support automation, decision making and cross-disciplinary collaboration among employees (Gunasekaran and Nathb, 1997; Hvam et al., 2011). With their help individual preferences are translated into correct and complete specifications during order acquisition and fulfilment, such as product details, price lists, bills of material, manufacturing instructions etc. (Forza and Salvador, 2002a). Due to their functionality, today product configurators are one of the most successful applications in artificial intelligence systems and can increasingly be found in the majority of industries (Felfernig et al., 2004; Stumptner, 1997; Tiuhonen et al., 1996).

At this point, a list of critical success factors may help to decide how to proceed with the analysis. These factors depend on the business environment of the company, its strategy and short or mid-term objectives. From an operational perspective, characters describing the current performance can generally be related to any of the of the in Section 1.2.1.1 customization domains; i.e. time, quality, cost or flexibility. Empirical studies have shown that even though relevant, often such measures are not usually been collected to a sufficient degree in organizations (Neely et al., 2005). In such cases it may be necessary to conduct an initial performance analysis of the measures of interest by for example using the activity-based costing (ABC) approach (Kloock and Schiller, 1997).

A hypothetical example of typical requirements for the specification process described in form of a gap analysis is shown in Table 2-2. In this example the performance of the current specification process is evaluated based on few major operational measures related to time and quality. Their result can be used as a basis for defining the desired future performance of the specification process. The difference between the current AS-IS state and the TO-BE state describes the gap to be addressed. Alternative scenarios may help to identify the preferable solution for the TO-BE specification process and how this can be supported by a CS with respect to cost and benefit estimations. Finally, an action plan can be used to break down the further activities in smaller deliverables and to estimate their resources and time consumption (Hvam et al., 2011). Typical activities can include the modelling of the product assortment, training employees, programming, maintenance and documentation.

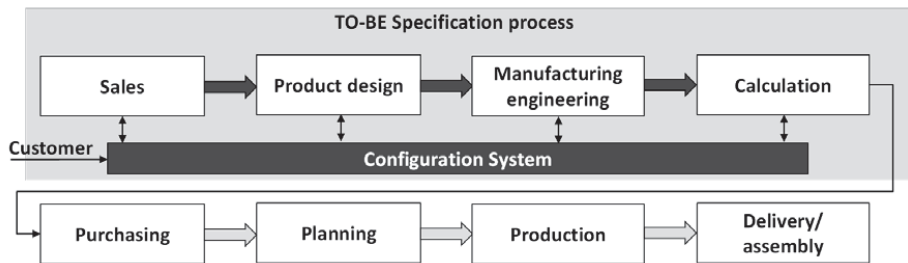
**Table 2-2: Hypothetical example of a gap analysis**

Category	Goal (TO-BE)	Present (AS-IS)	Activity
<b>Lead time</b>	Lead time for the elaboration of quotation max. 2 days	ON an average 8 days. Wide variations in lead time.	6 days, to be reduced by 75%
<b>Delivery certainty for quotations</b>	95% of all quotations must be made on time	50% of the quotations are made on time	45%
<b>Consumption of the resources for the elaboration of lists of operations</b>	30 minutes	4 hours	3,5 hours, to be reduced by 87,5%
<b>Quality of lists of parts in the production</b>	95% correct	70% correct	25%
<b>Optimization of products</b>	60% of incoming parts of the products must have been produced previously	30% of incoming parts have been produced previously	30%. The number previously produced parts is to be doubled.

### 2.2.3 Planning and implementing configuration systems

Once a particular TO-BE specification process has been selected and the need for a CS has been identified, in phase two to seven of the in Table 2-1 displayed framework a CS including the relevant product description has to be developed. The related tasks include the development of models representing the product assortment at hand and their subsequent implementation into a selected system. At the end of the framework the developed CS is to be incorporated into the TO-BE specification process. Figure 2-5 below illustrates how the CS may be used to assist the entire specification process, as explained by Hvam et al. (2008). The described TO-BE specification process is based on the generic ETO specification process introduced in Figure 2-4. Even though not particularly addressed by the authors, the figure indicates that potentially the entire specification process can be assisted by a CS. In this way, the configurator serves as the central communication platform, which covers the complete knowledge base needed to produce a bespoke solution. However, empirical examples of such scenarios have yet not been reported. Instead, the examples described in literature merely cover aspects of sales and to some extent address aspects of product design (Hvam et al., 2004; Tiihonen et al., 1996), touching upon areas of KBE (Elgh, 2012). General benefits from implementing the seven step framework can be found in (Haug et al., 2011; Orsvärn and Bennick, 2014). Another aspect refers to the implementation steps as such. Literature discussing strategies for CS implementation vaguely refers to the trial and error learning in form of a spiral model (Hvam et al., 2008). However, it remains unclear what potential scope should be taken when facing products with high complexity and the need for engineering. A recent empirical investigation of a company offering different product families ranging between MTS to ETO indicates that the support of big part of the ETO specification processes may be unfeasible or unprofitable to target from the beginning (Hvam et al., 2011). Consequently, a more rational approach may be to plan for a stepwise configuration implementation an agile development manner (Dingsøyr et al., 2012).





**Figure 2-5: TO-BE specification process assisted by a CS**

Source: Adapted from (Lars; Hvam et al., 2008, p. 20)

## 2.2.4 Benefits and risks from configuration system implementation

To give reasons and justification for conducting configuration projects, academia usually limits to proving the benefits from using already successfully implemented systems (Haug et al., 2012; Kropsu-Vehkaperä, 2011). To this end, apart from a number of well described case studies, more recently extensive surveys have been conducted. Table 2-3 below lists a result of a systematic literature research dealing with mapping the benefits for engineering oriented companies when using CSs to support their business, ordered according to the main authors. As illustrated, the studies propose a series of benefits which companies potentially gain from using CSs. In most of the cases, they are directly related to the operational performance of organizations, which in an operations management domain concerns cost efficiency, quality and delivery (Jacobs and Swink, 2011a). This understanding is also supported by research dealing with design automation methods working with self-developed KBE tools, where similar achievements could be demonstrated (Elgh, 2012).

**Table 2-3: Expected benefits from using product configuration systems**

Potential Benefits	Author										
	Ardissone et al. (2003)	Blecker et al. (2004)	Forza and Salvador (2002)	Haug et al. (2011)	Helo (2006)	Hvam (1999), Hvam et al. (2003, 2006, 2008)	Song et al. (2009)	Tenhiälä et al. (2012)	Trentin (2011, 2012)	Tiihonen et al. (1996, 2005, 2011)	Tseng Yang et al. (2009)
Shorter lead times	x	x	x	x		x		x	x	x	x
Improved quality of product specifications	x	x	x	x	x	x		x	x	x	
Better knowledge preservation			x	x		x			x		x
Fewer resources for product specification	x	x		x	x	x			x	x	x
Less routine work during specification process		x		x	x	x			x	x	
Less time for training new employees				x							
Improved delivery	x		x	x		x		x			
Improved handling of product variety	x	x	x	x	x	x	x			x	x
Improved order acquisition		x	x	x	x	x				x	x
Less quotation to order deviation				x		x					
Fewer resources for quotation process		x	x	x	x	x					
Reduced complexity in the specification process	x	x	x	x			x			x	x
Better product quality			x					x	x		
Better adopting new products and processes						x			x		

Despite the promising benefits, little attention has yet been paid on how to efficiently meet the wide-ranging challenges that need to be overcome when initially considering the implementation of CSs. To confirm the improved performance quantitatively, researchers mainly analyse the lead time performance and the quality of the specification process. While for the first aspect, management tools such as the discussed gap analysis or VSM have been suggested (Haug et al., 2011; Hvam et al., 2011), the latter aspect has been less examined (Trentin et al., 2012). A reason for that can be that in general quality can be defined in several ways (Hvam et al., 2008). Crosby (1980) for example approaches the term from four viewpoints, as he addresses the conformance to requirements, prevention, performance with no defects, and the price for non-conformance (Crosby, 1980). The latter form of quality may become a particular challenge of many ETO firms. As complexity of architectures rises, a systematic and standardized approach to acquiring and fulfilling orders becomes less possible (Bertrand and Muntslag, 1993; Grabenstetter and Usher, 2013). Sales, engineering and production activities require more coordination effort, causing more variability and thus contingency in operations (Konijnendijk, 1994). A negative effect of variability in operations is that generally degrades operational performance (Hopp & Spearman, 2008, p. 309).

Considering this multidimensional perspective to quality, it is eventually much easier to measure the lead time performance of an organization, than the quality with which specifications are done. Thus apart from counting the defects (errors) of companies' specifications, additional analytical methods have to be employed to assure reliable statements about their quality, in particular with the discussed price for non-conformance. Section 4.2 examines this aspect more thoroughly and discusses a method on several examples from praxis.

Apart from the confined investigation of potential benefits, when starting configuration projects, several supplementary risks need to be considered. Since performing configuration projects is a rather complicated task that covers a wide-ranging part of the customization domains (Haug et al., 2012; Kropsu-Vehkaperä, 2011), it is difficult to anticipate the accruing development and implementation costs beforehand. If for instance a project turns out to be more costly than initially expected, the risk of failure would be relatively high, as the management board might no longer be willing to support the investment. Implementing a CS usually affects the internal workflow of an entire firm, starting from the sales to the production department. Reorganizing established workflows would then typically demand significant changes in the business process of organizations, where CSs have to be widely accepted and used. If the resistance of change thereby outranges the promised benefits, the configuration project is very likely to fail. Strategies to promote higher benefit-to-cost ratios during the implementation of CSs are further discussed in the context of an ETO manufacturer in Chapter 4.

### 2.2.5 Accessibility and capabilities of configuration systems

Accessibility to state-of-the-art expert systems in academia imposes an additional limit to the progress of research within this area. Due to this rare and restricted use of the systems, advancements in configurator technology are seldom being adopted by engineering domains, thereby increasing the risk of a frequent reinterpretation of existing best practises (Jiao and Helander, 2006), or for the redefinition of well-understood capabilities for mass customization (Helo et al., 2010). Another common misinterpretation of configurators may come through term itself. Product configuration as such is often confined to the process of recombining existing building blocks of a modular product architecture (Jiao, Simpson, et al., 2007). Therefore, for many researchers and practitioners employing configuration software means to develop simple marketing tools, i.e. advanced (online) product catalogues with a fixed set of predefined and often static components, which can gradually filter out possible solutions (Brière-Côté et al., 2010). Hence, without further insight, the capability CSs is reduced to assist this elementary filtering process, thereby ignoring two important

aspects. First, modern model-based systems are able to employ a knowledge base of determinant or parametric elements which may cover a complex solution space tending to infinity (Felfernig et al., 2012). And second, configurators may alone or in combination with one or more supportive IT systems, e.g. computer aided design (CAD) or engineering calculation software, be used to assist design departments in solving a variety of customization and design automation problems (Orsvärn and Bennick, 2014). In fact, unlike often reported (Salvador et al., 2009), in praxis configurators are mainly implemented internally to partly automate the customization of industrial products (Haug et al., 2011). Besides they apply visual and interactive representations (dynamic and static) to guide users through the process of making valid solutions (Hvam and Ladeby, 2007). The individual functionalities of the software may differ, depending on the software provider, implemented inference engine and the way of reasoning. Software particularly beneficial for modelling complex architectures provide an object oriented modelling environment and employ constraints as part of their reasoning (Orsvärn and Bennick, 2014).

From an ETO perspective, the implementation of CSs may include additional challenges. Regardless their potential application, even for state-of-the art systems a trade-off in praxis may be to find the appropriate level of detail for the to be modelled product architecture. Is the implemented computer model of complex architectures too superficial for the underlying problem, the system would not automate much of the customization process, but leave the majority of the engineering work to manual adjustments (Brunoe and Nielsen, 2012). On the other hand, creating detailed architectures for e.g. entire plants may not be a feasible or even a possible task to do. Even if comprehensive product information is available from the beginning, it can easily take up to several years to develop the entire architecture and implement it in a system. Moreover, ETO products by definition involve additional engineering for which the outcome may not be known yet and hence may not be covered entirely by the expert system (Hvam et al., 2006).

## 2.3 Chapter summary

Drawing on literature, this chapter provided an overview of the MC concepts relevant for this research project. The term solution space was formally described in the context of the customization domains, to lay the foundation for the understanding of architectures. Subsequently, different approaches to MC were briefly described and established capabilities addressing the transition from mass production were assessed. Next, the design of the specification process was evaluated. An empirically widely tested procedure for the development of specification processes was described and different methods for their assessment and redesign were discussed. A particular focus was thereby put on the planning and implementation of CSs, as an essential part of the specification process support. A systematic literature study was included to identify stated benefits of implementing CSs. On the other hand, potential risks and limitations of the systems were elaborated. This investigation helped to answer elements of the second research question, in particular QR2.2 (What are expected benefits, risks and limitations when implementing CSs for ETO products?) from a theoretical perspective.

# 3 DESIGN FOR MASS CUSTOMIZATION

Chapter 2 established the required understanding of basic MC concepts and how they have been used to transform many mass producing firms into successful mass customizers. This was done by reviewing key literature and discussing relevant subjects. This chapter provides an overview of state-of-the-art of research on the development and management of architectures, as an essential element for the accommodation of customizable products. The chapter is structured in seven sections. Section 3.1 elaborates on the characteristics and development of architectures used for customization. This understanding establishes the background for a nuanced discussion on the appropriateness of popular modelling methods of architectures for single products (Section 3.2) and product family models (Section 3.3). Next, in Section 3.4 an extended modelling method is presented based on the developed requirements. Section 3.5 discusses approaches to the management of complex architectures and presents a consistent framework covering the discussed themes. Section 3.6 reflects upon the initially discussed MC capabilities from Section 2.1.2 and refines them based on the gained insight from Chapter 2 and 3. Finally, Section 3.7 provides a summary of the chapter.

## 3.1 The role of architectures

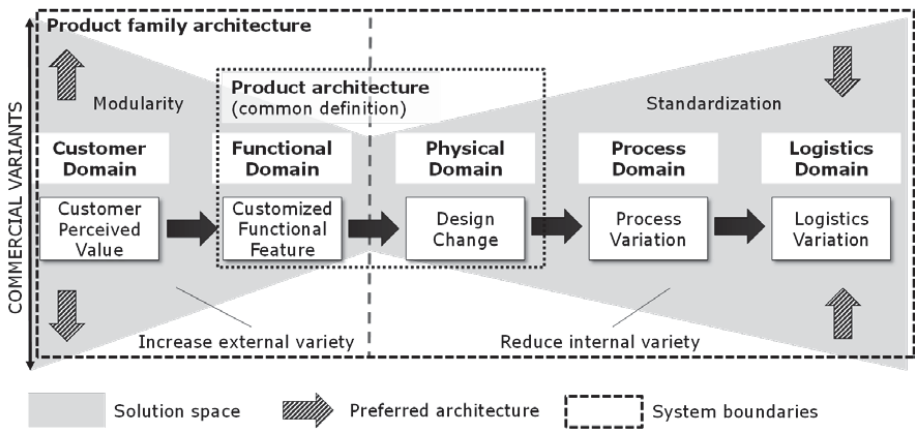
Operations management literature dealing with the implications of customization typically uses simplified or only theoretically explainable examples to discuss how product design may enable customization more effectively. Many researchers for instance argue that product modularity per se helps to limit the complexity and to reduce the cost for customization, without providing any particular qualification when products are seen as modular and when they aren't (Blecker et al., 2004; Duray, 2002). While a limited view on what constitutes a "good" design for customization may be enough in the context of simple mass produced products, the situation for ETO industries is very different. It requires a deep understanding of the underlying design principles of products and their related lifecycle properties, to be able to make any decision about variants possible. Engineering design literature is in this respect more precise and facilitates a comprehensive view on preferable architecture design for customization. The following sections review some of the basic concepts and popular methods for architecture design.

### 3.1.1 Utilizing preferred architectures for product family design and customization

#### 3.1.1.1 From product design to product family design

Handling and designing different products variants for customization is recognized by engineering design literature as being a costly and long-term process that includes unforeseen risks and uncertainties. It is typically not feasible for manufacturers to develop individual architectures for each niche market. Instead, product design, planning and production needs to shift focus from mastering individual products towards developing additional features at decreasing costs (Simpson et al., 2006). The planning for variants is facilitated

through the grouping and classification of similar functionalities and components into product families. This process is commonly known as the development of a product architecture. A widely used interpretation of *product architecture* has been introduced by Ulrich (1995), who states more precisely that architectures constitute: (1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; and (3) the specifications of the interfaces among interacting physical components (Ulrich, 1995). This definition has been described in the context of designing a particular product or product variant. When applying the concept of architectures to entire product families, the *architecture of a product family* then expresses how the functional units are related to the physical elements and the way in which these elements interact to create the desired product variants (Wie et al., 2007). Considering the whole value chain as defined in Section 1.2.1.1, it can moreover be stated that the processes and logistics needed for establishing these components should likewise be taken into account when describing a product family architecture (Jiao, Zhang, et al., 2007).



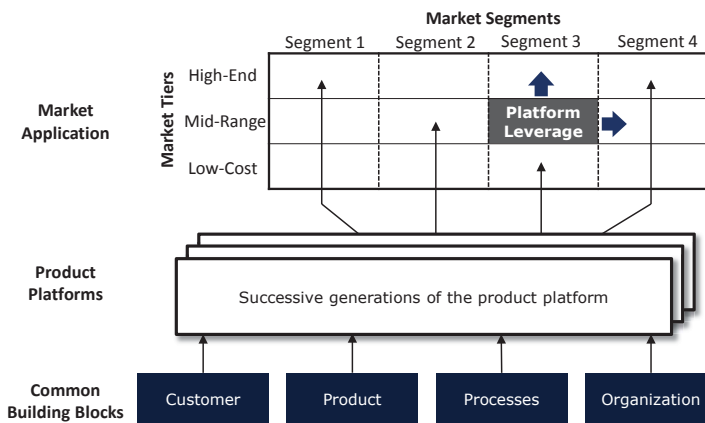
**Figure 3-1: Modularity, standardization and variety in product family architectures**  
Source: After (Erens and Verhulst, 1997)

Figure 3-1 illustrates this relationships between product and product family architectures along the reference framework of the customization domains. A general objective of designing “good” product family architectures (further mainly referred to as architectures) for customization is to capitalize on increased reuse of *common* elements across different products, without reducing the distinctiveness of features critical for the market performance (ElMaraghy et al., 2013). In particular, in variant-oriented design changing and adding elements within the architecture may have a strong impact on primary parts and functionalities. To reduce the risk for malfunction or part incompatibility, it is important for designers to understand the reconfiguration of an existing family design and to develop of compatible elements with preferably little impact on the remaining architecture (Alizon et al., 2007). Hence, the design of this so-called modular architecture is often employed to create of derivatives with different functionality and form, whilst obtaining economies of scale through a high level of communality between variants (ElMaraghy, 2005). This effect of modularity is indicated in Figure 3-1. Modular architectures are seen as a major enabler for being able to reduce the internal variety of organizations through standardization, while increasing of the external variety towards the market.

### 3.1.1.2 Balancing modularity and commonality with platforms

Modularity is a relative measure and describes the status of components relative to other components. There are different definitions modularity to be found in literature. The most

recent ones use a neural network approach to described a generic term for modularity, which can be used context independent. In a network of components, modules are tightly connected components inside a cluster and loosely connected to others (Sosa et al., 2007). The degree of *modularity* is then defined as the relative difference between the connections inside a module and to the others. Having a more modular architecture therefore means to have modules, which have relatively weak connections to other modules and can therefore be easier replaced to form different variants. Hence, a *preferred architecture* for customization is an architecture that makes it possible to obtain a large commercial variety and respectively large external solutions space with a reduced number of internal variety and therefore reduced internal solution space. When taking the decoupled system example from Section 2.1.1, this decoupling of the different variety within and among each of the domains essentially represents the highest possible modularity form that can in theory be obtained; this is when all elements of the system are independent from each other and can be recombined with the discussed function. The LEGO blocks example however clarified that in order to reduce the negative impact of the variety induced complexity, the preferred architecture is to reduce the internal variety. Therefore, instead of requiring different and independent components, processes and logistic activities to provide the high variety of LEGO blocks, the objective is rather to gain from as much as commonality as possible through standardization. Further details about modular drivers and possible effects can for example be obtained in (Ericsson and Erixon, 1999).



**Figure 3-2: The power tower as a strategic platform plan**

Source: Adapter from (Meyer & Lehnerd, 1997, p. 38)

According to Jiao et al. (2004) this reuse of common internal elements of an architecture is desirable. In architecture design the commonality of parts can in particular be exploited by the use of *product platforms*. With platforms, companies are able to attain efficient variant management, as they translate a large amount of customized functional features into fewer design changes (Jiao and Tseng, 2004). Hence, a key objective of a platform-based product development is to provide sufficient product variety to meet individual customer needs while maintaining economies of scale and scope within manufacturing (Pine et al., 1993). Meyer et al. (1997) define a product platform as “a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced” (Meyer & Lehnerd, 1997, p. 39). The authors further state the with the right scaling strategy of the platforms, companies are able to effectively adapt to changes on the market and yet keep their competitive advance across the entire product portfolio. The scope of product platforms therefore goes beyond the reuse of common parts across products, but may even promote their reuse across different product families. The platform concept as described by Meyer et al. (1997) is displayed in Figure 3-2 in form of a platform plan,



the so called power tower. A set of building blocks from four domains; customer, product, process and organization or logistics form a common platform for reuse across the chosen market application. Over time, different platform leverage strategies may then be adopted to expand the use of a particular platform (Robertson and Ulrich, 1998).

Based on this initial description of platforms, a vast amount of complemented research has been conducted in this context, where further extensions of the concept have been made to account for the entire value chain. From the perspective of platforms, process and logistics platforms can be described as a set of (production and supportive) processes that form predefined bill-of-operations and thereby enable the completion of process variations for a given customer order (Jiao and Tseng, 2004). The coordination between the process elements and the ordered product elements can be called variant derivation (Zhang et al., 2007). In order to reduce the complexity caused by the increase of product and process variety, a postponement or delayed differentiation of the unique variants (see Section 1.2.1.2) is desirable (Blecker et al., 2006; Forza et al., 2008).

Once a preferred product family architecture has been designed, to effectively address a wider range of customers with the experience of an individual value creation, additional establishment of configurators have to be employed (see Section 2.2). From efficiency perspective, customer-driven design relies on the systematic reuse of architectures that meet individual demands with configurations which are feasible in functionality and which fulfil the limitations of manufacturing. As discussed previously, the recent progress of CSs made it possible for manufacturers to integrate to a further extent the solution space into sales processes as a reuse strategy. Once implemented, product family architectures represent the knowledge base of model-based CSs. In this way, modern applications employ generic product architectures and sophisticated interference engines with search algorithms from operations research to display the exact propagation of design changes (Orsvärn and Bennick, 2014). To avoid the in Section 2.2.5 discussed misconception of the software's capabilities, this thesis therefore refines the definition of *configurators* as computer-based expert systems which use generic product family architectures to efficiently and effectively assist enterprises in their specification process.

## 3.1.2 The architecture design process for MC

### 3.1.2.1 From real world to computer model

The design of architectures and their subsequent implementation in configurators involves domain experts from different departments and often physically disconnected teams. On an overall level, companies need to create customizable product families, implement their architecture in a computer model, communicate and maintain the architectures and promote their functionalities to the market. Several researchers have acknowledged the related organizational challenges in architecture design and have proposed methods on how to arrange corresponding activities in a more systematic manner (Ardissono et al., 2003; Forza and Salvador, 2002b; Hvam et al., 2004). In engineering domains Pahl et al. (2006) address architecture design on several stages, from formulating customer needs to the construction of embodiment and detailed design (Pahl and Beitz, 1996). Corresponding to these different phases of development, Jiao et al. (1999) argue for an architecture modelling framework which in addition considers several views of a product (Jiao and Tseng, 1999). Yet other researchers promote a top-down strategy of the design process, which aims to connect customer requirements to scalable architectures based on platforms and modules (Meyer and Lehnerd, 1997; Simpson et al., 2001). At the same time frameworks dealing with architecture design for expert systems typically fall within the area of software systems and base their methods on the life-cycle of object-oriented software development as introduced by Booch (1986). Booch's object-oriented procedure was originally developed to handle the complexity of large software projects by breaking down the development work into phases

of object-oriented analysis, design, implementation and maintenance (Booch, 1986). To enable the representation of a large number of physical artefacts with components and variant combinations, related frameworks commonly build upon methods for modelling software architectures using the unified modelling language (UML) (Felfernig et al., 2000).

Although the UML standard proved to be particularly useful for defining entire product families, its application within engineering management remains limited. In consequence, synergies on coinciding aspects of architecture design are seldom being achieved. For example, the challenge of modelling different architecture views has been repeatedly addressed within the two domains and has resulted in comparable outcome (Brière-Côté et al., 2010; Haug et al., 2010; Jiao and Tseng, 1999). Moreover, advancements within engineering management are seldom adopted to software design and vice versa, in particular with regard to the formal computational management of structural properties in complex architectures (Lindemann et al., 2009). And second, the development of a product family architecture for expert systems is often organized within IT and product data management departments. The process is regarded as a liberally new modelling approach which is detached from any preceding design activities of the product development phase (Speel et al., 2001). This means that in praxis the design of architectures is not coordinated across the organization, leading to computer models which are very likely to differ from the original design intent of the engineers (Haug et al., 2012). Especially for more complex products, this lack of consistency increases the risk for providing undesired product variety to the market. As a benchmark report with more than 300 manufacturers of custom tailored products reveals, the top performing companies with engineering intensive portfolios try to overcome this coordination burden by better involving development engineers into the architecture design process for their CSs (Aberdeen, 2008). This suggests that a more integrated approach to mass customization is needed, which equally considers both the architecture design process and the subsequent implementation into CSs.

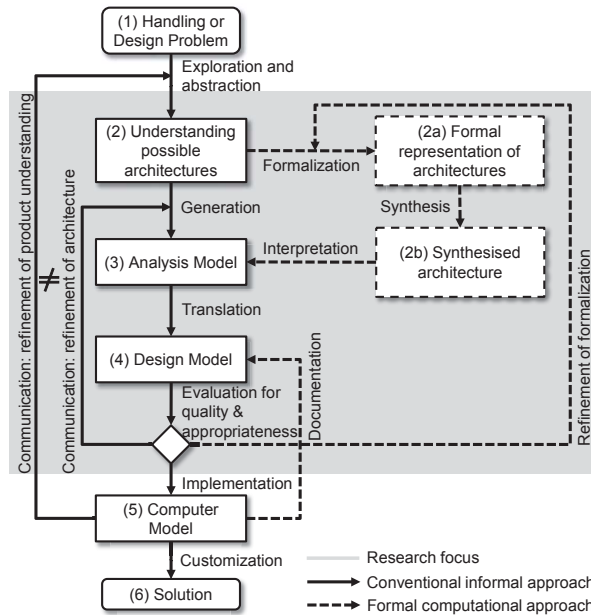
### 3.1.2.2 Informal and formal architecture design strategies

Figure 3-3 displays how the architecture design process may be realized in a consistent framework. The focus of this thesis is indicated by the grey area in the model and combines design aspects from engineering and software domain. The procedure is initiated by a design problem and ends with a customized solution created by the user of a CS. As indicated in the model, supporting methods can be informal, relying on subjective interpretations of domain experts, or formal, involving codable and systematic procedures. Widely used informal methods depend on human creativity and may include simple brainstorming principles (Osborn, 1963), and more guided brainwriting concepts (Heslin, 2009). However, architectures can be created in many different ways. The qualitative character of the design space makes it difficult for domain experts to develop new architectures, or even to be able to consider alternative solutions for a product family (Wyatt et al., 2011). If lacking a systematic guidance, domain experts often base their work on experiences from previous design problems. When a new design task occurs, they tend to commit early to familiar solutions which may be premature and not well suited for the underlying problem. This so called fixation effect restricts practitioners from constructing previously unknown yet potentially better solutions (Purcell and Gero, 1996).

In the same way, fixation has a detrimental impact on the quality of the architecture in the computer model. To guide developers in creating new models, modern configurators contain knowledge base editors and supportive debugging methods (Liao, 2005). They assist software experts in constructing executable computer models within the software environment, but fail to abstract, document and represent the product architecture so that it can be retrieved and communicated effectively (Li, Xie, et al., 2011). Hence, configurator experts have little or no possibility to collaborate with domain experts when developing computer models, which additively reinforces the fixation problem. Moreover, they have to



go through architecture models with potentially thousands of elements within the configurator and manually compare them with the previously developed architectures without being able to adequately abstract the underlying design problem.



**Figure 3-3: A consistent model for designing and mass customizing product family architectures based on informal and formal methods**

Source: After (Wyatt et al., 2011)

In contrast, as the complexity of the designs increases, formal approaches are becoming increasingly important. In complex design problems they are often based on computational models which are used to synthesize potential architectures (Cagan et al., 2005). In order to evaluate a solution based on a formal synthesis the architecture problem has to be made explicit, thereby providing a transparent and more reliable form of reasoning. In addition, proper documentation and knowledge representation methods may enable an intuitive comparison of architectures and hence increase the reliability of the expert system (Verhagen et al., 2012). The two alternative approaches may be organized along a five phase model of exploration, generation, evaluation, implementation and communication, which is based on the established development model of design science (Cross, 2008). Inspired by Wyatt et al.'s (2011) architecture design framework, the process can be described as follows:

- *Exploration* helps engineers to examine the handling of existing design or the work on a new design problem. Typically, product information can exist in many different formats, such as diagrams, tables, formulas, computer aided design (CAD) files, bill of materials (BOMs) etc. Different departments within a company may even have their own representations of products. By *abstracting* the relevant product information (1), engineers develop an understanding of possible architectures (2).
- Based on a created understanding of possible architectures, engineers *generate* a specific family architecture in form of an analysis model, which may be the same as previous solutions and further contain errors (3). Discussions on the product architecture during the object-oriented analysis may involve various domain experts coming from product design to sales and marketing. Since not all departments are necessary familiar to the

same technical detail of a product, often this is done by visually representing the product family in graphical models and describing the combinatorial possibilities in a way which is similar to the natural language. For instance, using pseudo-code for constraints instead of mathematic expressions, in form of 'component A has to be as wide as component B', makes the models more appropriate for a cross-disciplinary communication.

- The analysis model has to be *translated* into a design model (4), which is more suitable for the subsequent *implementation* into a computer model (5). The aim of this step is to adjust the representation language of the analysis model into a format which is common to the one of the final computer model of the configurator. Rules describing the combinatorial feasibility and solution principles of a product family have to be expressed in mathematical equations, making them readable and understandable by the software. In addition, the product family architecture may be extended with information related to the configurator design, such as the user interface, details on the implemented methods or the interaction with other IT systems. Depending on the experience of the project stakeholders, in praxis this step may not be strictly separated from creating the analysis model, but often involves further detailing of the architecture.
- The design model is *evaluated for quality and appropriateness* to determine whether the created solution fulfils the problem at hand at the best possible way. Has the architecture been accepted, the design model can be *implemented* as a computer model (5) in the CS. If not, the architecture is *communicated* to the design team, to iteratively *refine the solution*.
- Users (internal or external) of the CS can *customize* their solution based on the implemented computer model. If the offered solution space is either faulty (wrong configuration) or does not reflect the desired variety (missing or unwanted configuration), the computer model may be *communicated to refine the understanding* of the problem. Though both aspects are critical for the acceptance of the configurator, the latter becomes particularly important in markets where demands are frequently changing and enterprises need to keep pace with these changes. As with this approach, no mechanism is typically established to ensure the constancy between design and computer model, the two communication processes illustrated in Figure 3-3 do not necessary represent the same product architecture and are thus to be considered separately.

As discussed above, the generation and implementation phase of the informal approach may be critical for the quality of the obtained architecture. The dashed lines in Figure 3-3 illustrate how this can be avoided by a formal computational solution:

- The understanding of the possible architectures (2) can be *formalized* through a guided modelling environment and the representation of alternative architectures (2a).
- The computational methods assist domain experts in *synthesizing* a possible architecture (2b), which is then *interpreted* as an analysis model (3), and further translated into a design model (4). If the solution does not meet the evaluation requirements of the underlying problem, the development team may iteratively *refine the formalization*.
- Has the design model been accepted, it may be *implemented* as a computer model (5). To ensure the consistency between computer and design model, it needs to be *documented* and compared against the design model. *Communication* helps to refine the architecture and/or the product understanding, which may be internal (towards the development team) or external (towards customers). Since product architectures are typically developed iteratively over time, for large and interconnected models proper documentation and communication becomes particularly important. In such cases the documentation and communication of already developed implemented architectures is a prerequisite for any further development.

### 3.1.3 Requirements for a formal architecture synthesis approach

The majority of methods for formal architecture design synthesis are based on engineering management literature (Chakrabarti et al., 2011). They vary from numerical optimization approaches of partial design problems for single products (Ziv-Av and Reich, 2005), through heuristics for module optimization in product families (Jiao et al., 2008), to morphological analysis methods for incremental design improvements (Kurtoglu and Campbell, 2009). Methods considering entire products are often based on ontologies, i.e. grammars applied to graphs to display architectures (Schmidt and Cagan, 1997). A widely used technique for such graphs is to map architectures through their structure with nodes and links, i.e. to create an abstract representation of the underlying elements identified by their type and relations (Andreasen et al., 1995). The so called node-link diagrams express objects (components or functions) of the product and the edges stand for the connections or interfaces between them. The product architecture may be modified either through changing the structure of the model, i.e. by redefining the connections between elements, or through altering the objects as such. The latter may for example mean to add new components and/or functionalities to a product. Adjacency matrices provide an alternative well-organized and compact representation of elements and their relationships. As one of the first supporters of this modelling method, Steward (1981) applied adjacency matrixes also known as design structure matrices (DSMs) to display elements and their relationships (Steward, 1981). Based on his work, a number of additional (computational) matrix-based techniques have been proposed over the years (Eppinger and Browning, 2012). These two simplified grammar graphs can be used to create entire new architectures or to evolve existing ones. This is particularly useful, since architecture design is typically incremental, where products are upgraded over time and their components are reused in alternative or later products (Clarkson et al., 2004). Examples for computational design synthesis using structural grammar graphs can e.g. be found in (Lindemann et al., 2009; Wynn et al., 2010).

Research dealing with CSs has likewise recognised the need for a formal architecture design and implementation approach, where for example the handling of complex highly connected models has been addressed explicitly (Tiihonen et al., 1996; Wielinga and Schreiber, 1997). In particular the challenge of documenting and communicating entire product family architectures has been discussed in several studies (Haug et al., 2010; Hvam et al., 2005). The authors conclude that the complexity of the models makes it infeasible to update and visualize each model manually without any guidance, but requires dedicated methods and software tools. At the same time, comparable computer-based design synthesis methods as suggested for single product design are yet missing. Important contributions of informal approaches to be mentioned in this context include the product family architecture (PFA) approach (Jiao et al., 1998), the use of class diagrams and CRC cards (Aldanondo et al., 2000), the frames parts components (FPC) model (Magro and Torasso, 2003), and the product variant master (PVM) (Hvam et al., 2005). The majority of the so called generic methods use variations of object-oriented modelling based on the UML standard to describe hierarchical composition of elements (generic part-of-structure), their possible variants (kind-of-structure), and their combinatorial interfaces to other elements (collaborations) (Felfernig et al., 2000). The UML notation includes the object constraint language (OCL) as an expression language of how elements in a model are combined with each other. Due to their additional notation, generic methods can be regarded as an extension to the structural representation of the grammar graphs discussed above. Further details about the slight differences of the methods will be discussed in Section 3.3.

Despite the advantages of computational synthesis methods, their application in industry has been limited. This may be partly explained by the mismatch between the needs for such methods in architecture design praxis and the systems developed hitherto. To overcome this, related studies have recently proposed general requirements that address the described aspects of formalization, synthesis, interpretation and refinement for single architecture design (Wyatt et al., 2011). Since the design process is typically incremental, a

formal method should guide engineers to specify initial architectures as a starting point for synthesizing new solutions. The corresponding design problems may then be decomposed into smaller interlinked sub problems, represented by the relevant model elements, while the possible solution space should be declared explicitly through constraints. For instance, architectures representing the energy consumption of diverse production plants might not necessarily include all elementary machine elements, but rather consider major factors (components and properties) and their ranges influencing this value. Next, synthesized architectures should be presented and evaluated through their structural features which have favourable or unfavourable effect on any lifecycle objectives of the product family. Frequently used metrics for example investigate the commonality and modularity of different architectures (Sosa et al., 2007). The problem formalization may then be refined by the engineers as a consequence of their interpretation of the synthesized solution. The obtained architecture is documented to ensure its consistency throughout development and implementation, and is communicated to modify the understanding of the problem. For instance, new production lines might need to be added to an implemented model of a plant, for which the already created architecture would be required.

**Table 3-1: Requirements for formal architecture synthesis**

Category	Requirement	Content
Formalization	F1 Incremental design	Guided architecture creation as a starting point for synthesis
	F2 Problem decomposition	Abstract sections and focus on relevant scope
	F3 Problem-specific architecture	Represent relevant elements in ways that fit the problem
	F4 Declarative evaluation	Declarative constraint-based representation of the solution space
Interpretation	I1 Interpretation support	Present synthesised architecture and allow for further evaluation
	I2 Feature-based evaluation	Specify structural features according to lifecycle objectives
Refinement	R1 Refinement of formalization	Support modification of the problem formalization
Documentation	D1 Consistent architecture design	Ensure architecture consistency throughout design and implementation
Communication	C1 Complete and correct representation	Consider graphically all structural aspects of product families

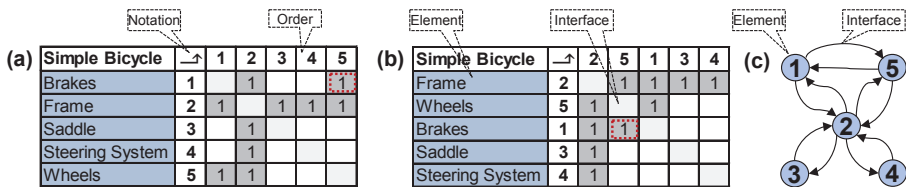
Table 3-1 summarizes the requirements for a computational design synthesis as proposed by Wyatt et al. (2011) and complements those with the context specific aspects of *documentation* and *communication* of product families. Since the described recommendations and the underlying graphical methods are reduced to the special case of designing single product architectures, they have to be tailored to the context of this paper. The most profound aspect arguably addresses the ability to model, synthesize and communicate entire product family architectures using the discussed graphical grammar approach. To obtain a deeper understanding for a supportive method, Section 3.2 and Section 3.3 use an illustrative modelling example to briefly address the limitations of the existing grammar graphs.

## 3.2 Single product models

### 3.2.1 Adjacency matrices

Generally speaking, matrix-based modelling techniques help to classify the product structure, i.e. the relationship between elements identified by their type. In accordance with the definition in Sect. 3.1.1, architectures are modelled as abstract description of the entities of a system and their relationships between each other. The DSM format is an adjacency matrix that is employed to display relationships of such entities (functions or components) of the same type for single products. Each element is represented by a row and a column, while entries in the DSM indicate a link from one node of the matrix to the other. Two different conventions exist in literature to describe the direction of a link. The IR/FAD convention uses element inputs shown in rows and outputs in columns. The IC/FBD convention of the other hand shows element inputs in columns and outputs in rows. The two notations are based on the same information, where one is the matrix transpose of the other (Eppinger and Browning, 2012).

To illustrate the functionality of the DSM method, the letter notation is shown in a simplified modelling example of a bicycle provider. As model (a) in Figure 3-4 displays, the bicycle consists of five main components. All elements have been ordered alphabetically and their interfaces to each other are shown through the entities of the DSM. In this way the product structure consists of interconnected components shown as a squared intra-domain matrix. Alternatively, to represent the structure of two different domains within the matrix, e.g. components and functions, the additional domain may be listed on the other axis. This variation of the DSM is also called domain mapping matrix (DMM) and is based on the same modelling notation as the DSM. The DSM layout requires product elements to be listed strictly on the horizontal and vertical axes, making it a rather rigid but at the same time very compact and scalable way of describing structures of single products (Abuthawabeh et al., 2013). This well-defined arrangement has proved to be particular useful for computational analysis methods. For example, a very popular way to identify potential modules is to cluster the links between elements in chunks. This method is illustrated in model (b) of Figure 3-4. The order numbers in the DSM indicate how the elements have been rearranged compared to the alphabetical order to form a potential module.



**Figure 3-4: Different analysis models of a hypothetical bicycle, (a) DSM (alphabetical order), (b) DSM (clustered), and (c) a node-link diagram**

Adjacency matrices are used in a number of cognate methods. Through Quality Function Deployment (QFD) and the Axiomatic Design (AD) method (see Section 1.2.1) designers can use a series of inter-domain matrixes (Malmqvist, 2002) to transfer the requirements (the voice of customer) into specific product attributes, engineering characteristics, possible design solutions and manufacturing activities (Suh, 2001). Both methods provide guidelines for designers to make technical decisions more systematically, with the objective to design customer satisfaction and quality assurance into the product prior to production (Hung et al., 2008). Successfully implemented, such modelling methods have e.g. helped to increase competitiveness, lower start-up cost, and shorten design cycles (Vallhagen, 1996). Further analytical techniques around the DSM have been developed to assess, reorganize, and cluster relationships between elements (Pimmler and Eppinger, 1994). In order to improve the analytical capabilities, the DSM method has since its introduction been extended, modified, and integrated into other matrix-based approaches, such as the previously described QFD and AD methods (Guenov and Barker, 2005; Hung et al., 2008). From a solely inter-domain matrix with a limited capability of representing the nature of the relationships, over time the DSM method has increasingly been used on various intra-domain problems in form of the DMM, often in combination with fuzzy logic methods (Ko, 2010). Such DSM tools have been used from reorganizing static and time-based relationships (Browning, 2001), to supporting planning and scheduling activities (Shi and Blomqvist, 2012).

### 3.2.2 Network graphs

Network graphs, or often called node-link diagrams offer an alternative increasingly popular graphical representation of product structures, as described in Section 3.1.3. Initially such graphs widely been used in social network analysis studies with the purpose of characterizing the nature of social relationships among a set of actors (Freeman, 2004). Each actor within a given network is represented in a node and arrows between the nodes stand for links between them. To display their relationships, the nodes of a model can be placed

freely within the entire two-dimensional space, making this type of graph very flexible in layout. Especially for large models with many nodes, this flexibility can be very convenient. Model (c) in Figure 3-4 illustrates the bicycle example in form of a standard node-link diagram. As indicated by the layout, the frame is central for the entire structure of the model. It provides input to all remaining components and at the same time is connected through the same amount of interfaces from them. Depending on the actual analysis problem, a rearrangement of the graph allows the user to visually access only relevant network area, leaving out less important aspects unconsidered. Additional colour and distance coding may help to display social clusters and the strength of individual relationships. An extensive study on algorithms for drawing node-link graphs can for example be found in (Battista et al., 1994).

### 3.3 Product family models

Network graphs combined with matrix-based modelling techniques are strong in handling the evaluation of customer driven requirements and a vast amount of static and time-based relations. As long as the relations are described on the same level of abstraction and the information flow goes from the customer domain to the process domain (Suh, 2001), the methods obtain powerful analytical qualities. However, the drawback of such techniques is that they hardly support platform design and product redesign (Farrell and Simpson, 2010; Malmqvist, 2002), which is, as previously discussed, a prerequisite for today's product development for customization. The following sections discuss briefly current approaches more suitable for developing entire product families.

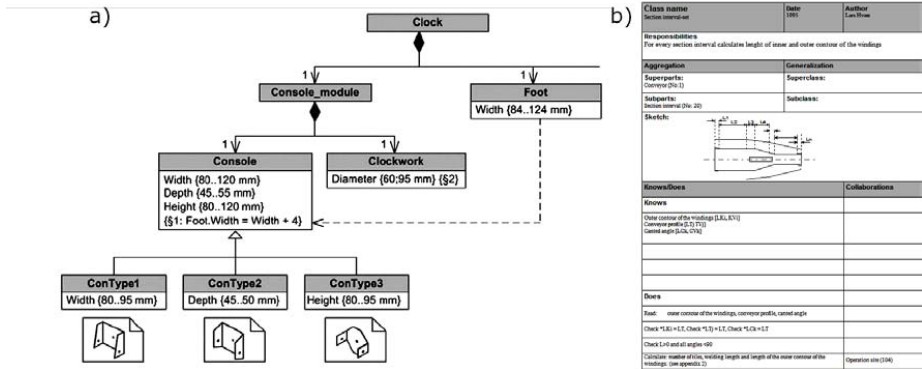
#### 3.3.1 Class diagrams and CRC cards

The challenge of modelling product knowledge for product families has been discussed by several authors and alternative representation techniques have been suggested (Hvam et al., 2008). In the majority of cases, the proposed methods make use of the Unified Modelling Language (UML) standard for the representation of the product knowledge and in particular of the information model (Felfernig et al., 2000). Aldanondo et al. (2000) for example introduce a combination of class diagrams, constraints expressed with natural language, as well as a number of inter- and intra-domain matrixes depicting the relationship between product components, operations or attributes (Aldanondo et al., 2000). Chao and Chen (2001) propose the use of a "general design" model, which expresses the relationship between components and assesses their ability for a physical assembly before production (Chao and Chen, 2001). Even though not discussed by the authors, the model makes partly use of the UML standard, to for example describe decomposition or cardinality. Also Magro et al. (2003) investigate the possibility of providing a sufficient model for the representation of the product knowledge (Magro and Torasso, 2003). The authors suggest a Frames Parts Components (FPC) model, as a means of describing the relevant product knowledge. The mentioned technique can be seen as a modified UML model with a reduced syntax for the expression of e.g. aggregation and generalization structures. Through its simplification, the authors argue for its visual support of sequential configuration algorithm examples. However, it remains unclear why the given and more comprehensive UML standard would not be at least just as suitable for the discussed configuration problems. Alternative methods have e.g. proposed the use of feature or functional hierarchy trees (Jinsong et al., 2004; Tseng et al., 2005). Based on such an initial meta-modelling of product functions, a more detailed configuration model is then acquired with class diagrams using the UML standard.

Figure 3-5 a) illustrates the modelling technique on a hypothetical example of a clock based on the example provided by (Haug et al., 2010). This example shows a part-of-structure consisting of foot, console and clockwork components. The console comes with three different kinds in form of a kind-of-structure. Each component is shown as a class consisting of a number of attributes, defining the behaviour of the component. Part b) of the figure



displays a CRC card of a component. The card inter alia states the responsibility for the component, a date, author, the hierarchical position within the UML diagram, the included attributes and constraints and a sketch showing the component. Further details about this modelling technique can e.g. to be found in Felfernig et al. (2000) and Hvam et al. (2003) (Felfernig et al., 2000; Hvam et al., 2003).



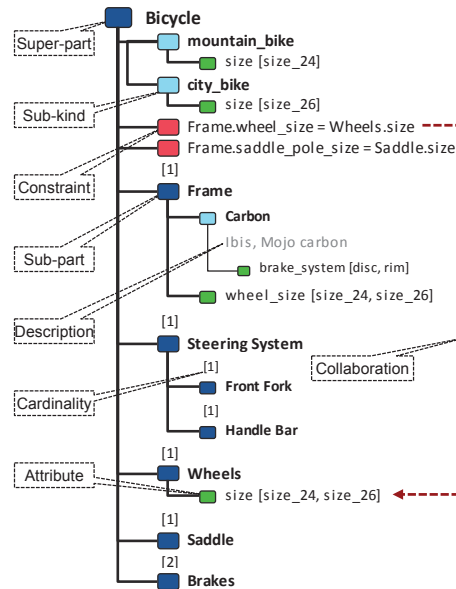
**Figure 3-5: a) a hypothetical class diagram example, and b) corresponding CRC card**  
Source: Adapted from (Haug et al., 2010)

The in Section 3.1.3 introduced notation of the PVM is based on the UML standard. It will in the following be used as a representative technique for a more comprehensive discussion on generic product models.

### 3.3.2 Generic product models for configuration systems

Figure 3-6 displays an example of the bicycle model expressed in the PVM notation. Similar to assembly models in computer aided design (CAD) systems, the model imitates the aggregation of elements through a hierarchical list connected with lines. The different colour codes represent the element type and the letter size indicates the corresponding hierarchy level. In general there are four different element types in a model: *parts* (functions or components), *kinds* (variants), *attributes* (properties), and *constraints* (rules). Each part and kind element stands for an *object* or *class* in the model. As an example, a wheel is an object in the model and a different wheel type is modelled as a separate object. The character of an object can be explained by attributes and constraints. *Attributes* are defining the properties of an element, i.e. length or width of a wheel, while the constraints are specifying how these properties operate within the product.

An important difference between *parts* and *kinds* is that parts can have both sub-parts and sub-kinds, while kinds may only include other sub-kinds, e.g. a van may be a family van or a transporter. The *cardinality* of parts is indicated by an index above each part. It defines how many times a particular component is to be found in the model and whether this component is optional (*0,1..n*) or mandatory (*1..n*). To illustrate the representation of hierarchies and variants, further details have been added to the bicycle model. The steering system of the bicycle can for example be described as the *aggregation* of a front fork and a handle bar. If viewed separately, each of the two components has an individual set of *attributes* and *constraints*. For example, the front fork has a clamp diameter that needs to fit with the wheels and the handle bar requires a certain type of brake system. Only in combination however, they create the required functionality for steering. As shown with the DSM technique in Figure 3-4, without this part-of structure we would have to decide which level to focus on at the first place, leaving out many other essential aspects unrevealed.



**Figure 3-6: PVM example of a hypothetical bicycle family**

The principle of constraints can be illustrated on two additional examples which have been included on the top level within the model. Complying with the requirements for a design model in Section 3.1.3, the constraints use attributes with mathematical equations to specify the geometrical relationship between the frame, the wheels and the saddle. Another important feature of such object-based models is the concept of *inheritance* and *encapsulation*. *Inheritance* means that the sub-kinds of elements inherit the generic properties of the super-element. For example, all bicycles consist of the same major components shown in Model (c). A mountain bike however may have a particular wheel size. *Encapsulation* on the other hand restricts objects at the same hierarchy from interfering with each other's properties. This means that a relationship between two components from the same hierarchy can only be expressed by constraints on the parent object. In this case, the bicycle frame has to fit with the wheels and the pole size of the saddle has to fit with the equivalent size of the frame, which has to be listed directly under the super-part of the model, as indicated by the dashed arrows in Model (c) in Figure 3-4. In object-oriented modelling these interfaces are referred to as *collaboration* or *association* between two objects.

In accordance with the common modelling environment of modern model-based expert systems (Acatec, 2014; Oracle, 2014; Tacton Systems, 2014), typically the PVM notation provides no standard visual representation for such a connection. Hence, because all interfaces between components are expressed through constraints, the generic approach alone proved to be disadvantageous when it comes to documenting and analysing the structural properties of product architectures (Bodein et al., 2014). As studies within the automotive industry show, especially for complex products designers and software engineers found it difficult to identify the relevant relationships among product elements, which creates additional challenges for changing and verifying existing architectures (Salehi and McMahon, 2011). Moreover, the extended syntax of the generic methods requires some experience in creating valid architectures. Modelling mistakes can easily occur if no systematic guidance through dedicated modelling tools is provided, which however are missing to date. In result, incorrect generic models can sometimes even be observed on examples provided by literature, where for instance inheritance has been ignored (Haug et al., 2010).



### 3.4 Evaluation and extension of architecture design methods

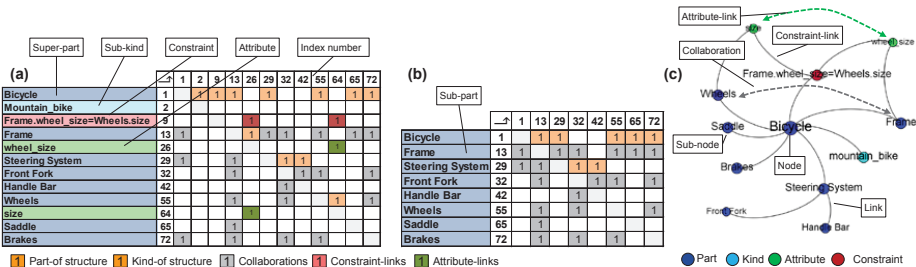
It is notable that when considered separately, many of the requirements in Sect. 3.3 cannot be fulfilled with the modelling methods discussed above, in particular:

- Grammar-based methods are by definition procedural and qualitative and need to be supplemented with metrics to obtain a descriptive explanation of the design problem (Requirement F4). Yet existing methods apply only for single products (Lindemann et al., 2009), giving the need to develop new methods and formalization procedures (Requirement F1).
- While several clustering algorithms exist in literature (Steward, 1981), this simple example also shows the limitations of such a method. Despite the small number of major elements, the components of a bicycle are connected in ways which do not allow a creation on any obvious modules. This limitation is often compensated by emphasizing on the visual display of structures (Requirement F2). Here, matrix-based representations have proved to be more suitable for most of the tasks in large and dense graphs (Ghoniem et al., 2005), which are very likely in the context of this study. Due to their rather restricted yet scalable layout, DSMs are applicable for products consisting of many interconnected components. As the layout of node-link diagrams is less prescribed, in complex product structures nodes and edges tend to overlap in ambiguous ways, making it challenging to navigate through the network and to identify patterns. However, if used properly in a dedicated software, a network representation with nodes and links is still more intuitive graphical representation and better suited with respect to finding paths between two nodes (Keller et al., 2006) (Requirement F3). Nevertheless, the two methods do not consider any representation of hierarchical compositions or variants, making them being too simplistic and impractical for modelling product families or any form of customization (Requirement C1) (Keller et al., 2006; Malmqvist, 2002).
- The discussed grammar graphs as such do not provide any information about the nature of the identified interfaces. To obtain more detailed understanding about possible features, additional external metrics (Requirement I2) and interpretation support (Requirement I1) is needed. This may be partly overcome with the extended notation of the generic models, such as the PVM. However, these models do not visually represent interfaces (collaborations) between components (Requirement F2), but rather use mathematical equations to express such through constraints (Requirement C1). Furthermore, the extended modelling notation requires additional guidance to obtain correct architectures (Requirement F1).
- Documentation is not explicitly supported by the existing methods but requires additional methods for that, increasing the risk for obtaining an inconsistent architecture design (Requirement D1).

The evaluation of the methods suggests that many of the requirements can be addressed explicitly by extending the existing notation of the relatively simple grammar based approach of DSMs and node-link diagrams. Especially Requirement F2, F4 and C1 can be directly met with a modelling technique which includes aspects of the generic grammar but which also provides a complete graphical representation of structures. Figure 3-7 presents how such an extension may be realized and corresponds to the common perception that multiple views of an architecture help to better understand the underlying design problem (Keller et al., 2005) (Requirement F3). The so called integrated design model (IDM) combines the different functionalities of DSM, node-link graphs and PVM into a consistent representation form. Model (a) in Figure 3-7 shows the generic structure of the bicycle into a matrix format (generic DSM). In addition to the main components from Figure 3-4 shown on page 49, rows and columns in the model may include sub-parts, kinds, constraints and

attributes. Entries in the matrix are used to express existing interfaces for part-of structures, kind-of-structures and collaborations. The scalable layout of a DSM further allows to consider two additional types of interfaces. *Constraint-links* define which attributes are being used in this particular constraint, while *attribute-links* display the connection between these attributes. Accordingly, collaborations exist whenever there are constraints causing an interface between two objects. It is worth noting that interfaces caused by constraints are by definition symmetrical, which in the example means that both frame and wheels have to fit to each other. Hence, entries for attribute-links and collaborations appear on both sides of the matrix diagonal.

The extended notation of the generic DSM enables users to *abstract* the underlying architecture design problem (Requirement F2), which may be done by: (1) changing the *level of detail*, i.e. connections represent the architecture at any level of granularity, and (2) changing the *scope*, i.e. to focus on a particular set of elements, without altering the remaining architecture. The principle of abstraction can be demonstrated by comparing Model (a) and (b) in Figure 3-7. While the first model is to some extent showing a higher level of detail of the entire model, Model (b) displays the same generic architecture of the bicycle family in a fully collapsed format, which is indicated by the visible elements and their index numbers. Especially for large graphs it can be very useful to create an initial overview over architectures by filtering out details in the model, without taking away any existing interfaces. The same generic structure can be expressed by analogy with a generic node-link diagram. To limit the discussed risk of having overlapping elements and connections in large and dense graphs, Model (c) narrows the representation of interfaces to the essential aspects. Hence, part-of-structures, kind-of-structures, and constraint links are expressed as previously described, leaving out redundant connection types (dashed arrows). Engineers can benefit from the graphical advantage of quickly identifying patterns and following important paths in the model (Requirement F2), without losing the required understanding for the present interfaces. The context of interfaces is preserved by using the original naming of all elements, which may be particularly important when investigating the cause of collaborations between two components (Requirement 3-4).



**Figure 3-7: Different views of a generic product structure, (a) generic DSM (partly collapsed), (b) generic DSM (collapsed), (c) generic node-link diagram**

A method to support product family architecture design and customization based on the requirements in Section 3.1.3. will be presented and subsequently tested on a practical case in Section 4.4.5.

### 3.5 Managing and representing complex architectures

Architectures modelled as a connection of elements for single products or for entire product families imply per se little or no information about a particular condition of the architecture quality with respect to any lifecycle objectives. As discussed in Section 3.1.3, to formally evaluate synthesised architectures, it is necessary to consider quality indirectly through the

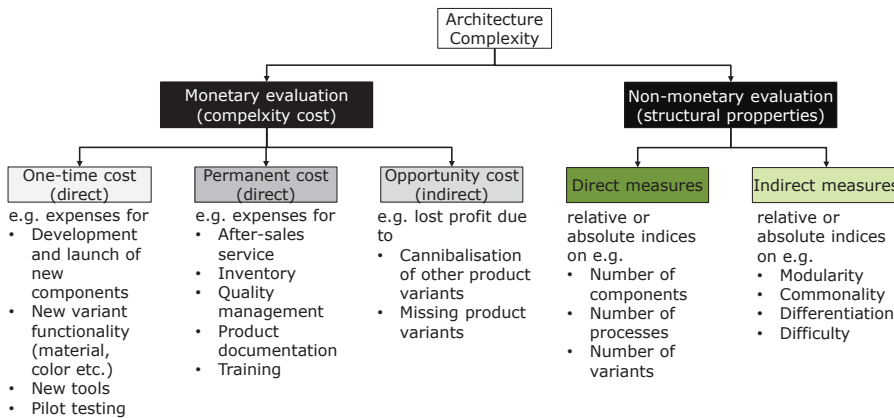
presence of additional features. The following sections deal with aspects of interpreting and refining synthesised architectures as a part of the strategic management in organizations.

### 3.5.1 Managing complexity with synthesised architectures

#### 3.5.1.1 Evaluating the complexity level of architectures

The growing importance of product customization (see Section 1.1.1) has led to a number of frameworks aiming at providing guidelines and support for handling and reducing the imminent increase in complexity. Complexity management strategies discussed in academia are generally referring to MTS or ATO products and address any of the three areas; product portfolio, product and value-chain processes (Götzfeld, 2013). A common aspect across all approaches is the importance of a clear and transparent understanding of the underlying architectures. Well defined architectures support the understanding of economic effects of variants and help to decide upon activities aiming at reducing their impact on complexity. Figure 3-8 below provides an overview of possible ways to estimate the impact of variety. As discussed in Section 3.1.3, in engineering design domains often structural properties of elements in single products at the individual and group levels are employed as indicators for a relative or absolute complexity evaluation (Kreimeyer and Lindemann, 2011). Measures directly referring to a complexity function typically include a linear relation between a complexity level and the increase in product components or their diversity (Patzak, 1982). To cover the entire architecture, recent contributions include additional lifecycle related measures, such as the number of suppliers or processes needed to obtain a certain product variety (Götzfeld, 2013). While this approach appears to be rather simplistic, it helps to quickly obtain a understanding of the solution space contributing to the commercial variety. Indirect measures focus on structural more sophisticated characteristics of an architecture modelled after social network analyses, such as modularity or commonality (Sosa et al., 2007). However, since the provided examples are typically taken from an MTS perspective, the suggested measures predominantly refer to one particular product variant at a time. Comparable measures for entire families have yet not been reported, in particular not with respect to ETO products. A detailed overview over related complexity measures for single products can for example be found in (Sinha and de Weck, 2013).

Operations management literature on the other hand tends to seek monetary approaches to approximate both the direct and indirect “complexity cost” of a variant (Wilson and Perumal, 2009). Cost immediately related to the introduction and maintenance of variants may be regarded as direct complexity cost. They may occur when for example a new variant is being developed and produced. This variant may require additional quality management, different tooling, more inventory or new material. Some of these cost, like material or labour may be directly related to a particular variant, others need to be allocated proportionally as overhead cost (Anderson, 1995). Alternatively, the loss of profits due to a cannibalization effect of a variant may as well be seen as a complexity cost factor (see Section 1.1.2). In addition, unfulfilled needs due to missing or wrong variety may likewise be regarded as contributing indirectly to an increase in complexity cost (Rathnow, 1993). All monetary and non-monetary methods are closely interlinked with each other, as any additional complexity cost automatically arises from a structural change of an architecture. Yet integrated approaches covering elements from both monetary and non-monetary domains are rare, indicating the strong dichotomy of the topic (Geraldi et al., 2011).



**Figure 3-8: Approaches to evaluating the complexity level in organizations**

Source: After (Homburg and Daum, 1997; Kreimeyer and Lindemann, 2011; Krinner et al., 2011; Schuh et al., 2008)

The transparent and therefore trustful evaluation of a current state of complexity plays an essential role for the effectiveness of management (Closs et al., 2008). As the obtained results are often new to the organization and accounting systems are not monitoring or documenting many of the listed aspects (Kloock and Schiller, 1997), a reliable basis for further activities is particularly critical for a successful management. Once the level of complexity has been evaluated to a sufficient degree, specific activities addressing it are to be taken. Comparable to the diverse ways of evaluating a current complexity level as such, there are a number of opposed methods of how to handle or potentially reduce the identified complexity (Lindemann et al., 2009; Scheiter et al., 2009). Inspired by Bliss (2001), a generic approach covering both monetary as well as non-monetary evaluation methods may be described based on Figure 3-9 below. The approach presents four phases in form of a sequential and cyclic method. Each of the steps may be conducted separately, however, due to interdependencies between the steps a combined implementation can be recommended.

### 3.5.1.2 Handling time-independent complexity

This *first phase* emphasises the removal “bad complexity”, i.e. of any redundant variety of components, processes, machineries etc., which is not strictly necessary to obtain the requisite variety, as defined by Ashby (1956) (Ashby, 1956). Such excess in complexity is likely to occur as a consequence of the correlated complexity increase throughout the strategy of differentiation. In accordance with Suh’s complexity definition, this can be explained by the occurrence of real complexity. Real complexity can be seen as an autonomous aspect, which can be eliminated, without reducing the provided commercial variety to the market. Component substitution, standardization, functional or horizontal integration of business processes are seen as some of the ways to address these inefficiencies (Marti, 2007). Other less obvious approaches may include the creation of pull processes through postponement to reduce any inefficiency in inventory (Brun and Zorzini, 2009), and process segmentation to separate between the handling of ETO, MTO and ATO products (Rudberg and Wikner, 2004). The resulting effect on the architecture can be formally described with direct structural properties, where e.g. the number and diversity of production steps needed to manufacture a particular variant may be further analysed. Additional methods, such as VSM (see Section 2.2.1) can help to identify and reduce redundancies throughout the value chain towards a preferred architecture (Hvam et al., 2011). In cases where the design activities are difficult to be mapped, relationships can be examined indirectly through the study of component dependencies (Daniilidis et al., 2011; Ulrikkeholm, 2014). The effect of this phase may result in a slight decrease of the current degree in complexity level  $C(A)$  towards an

optimum level (from  $C(A_1)$  to  $C(A_2)$ ), potentially leading to reduced cost  $C$  (from  $C_1$  to  $C_2$ ) and hence to an increase in profit  $P$  (from  $P_1$  to  $P_2$ ).

In *phase two* the offered variety can be reviewed under the aspect of changing customer requirements and technological progression (Rathnow, 1993). A portfolio that better matches with the current market demands is likely to generate higher revenue  $R$  (from  $R_1$  to  $R_2$ ) (Kotler, 1989). Such a portfolio reduces the gap between the design range and optimum system range, or in other words the imaginary complexity. Combined with a relatively stable cost curve, this would affect the profit function to a higher frontier (from  $P_1$  to  $P_2$ ). Concurrently, the indirect cost of not meeting the customer demands may be stressed with an effect on the cost curve. However, in practise the required complexity cost may be more difficult to estimate or measure, than a potential increase in revenue.

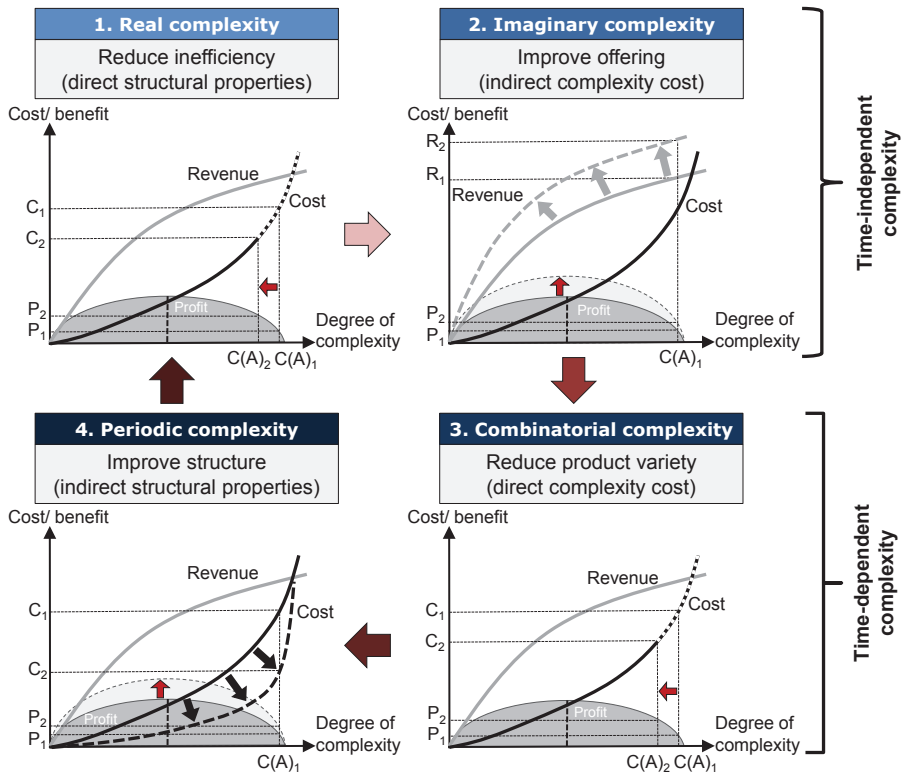


Figure 3-9: Generic complexity management approach

### 3.5.1.3 Controlling time-dependent complexity

*Phase three* of the framework focusses on reducing the unprofitable product variety offered to the market. The complexity trap and system variability (see Section 1.1.2) causes the design range to move constantly away from the system range, which increases the time-dependent combinatorial complexity. Here, a monetary approach based on contribution margins is often used to distinguish between preferred and undesired variety (Wilson and Perumal, 2009). Consistent with Ashby's requisite variety definition, product variants are thereby seen as the driving argument for having a related value chain process. Unprofitable variants are either substituted or their prices are adjusted according to the correctly allocated complexity cost. The objective of this variety reduction is to move the degree of complexity

$C(A)$  closer to the optimum level (from  $C(A_1)$  to  $C(A_2)$ ), again potentially leading to reduced cost  $C$  (from  $C_1$  to  $C_2$ ) and hence to an increase in profit  $P$  (from  $P_1$  to  $P_2$ ). In many business related literature this particular step of the framework has drawn a lot of attention (Byrne, 2007; Scheiter et al., 2009; Vesterby, 2008). The reason for this may be due to the fact that identifying “true” cost picture for a particular variant is a much more tangible and simple way of evaluating the effect variety has on profits, where no particular understanding of the underlying architecture or production methods is needed. A common path for related method is the reduction of such architectural elements to their essential cost figures with respect to handling (e.g. production and documentation), time (e.g. inventory time) or space (storage requirement) effort (Wilson and Perumal, 2009), disregarding any hierarchies and interdependencies. The challenging exercise of this step lies however in correctly allocating the overhead cost to variants (Blecker et al., 2006).

In contrast, *phase four* uses non-monetary measures to identify structural properties of a current architecture and to define strategies to improve this structure through e.g. modularization, standardization and communality (Kreimeyer and Lindemann, 2011). Much of the engineering design related literature deals with defining and calculating structural measures and subsequently finding ways to improve them towards a synthesised architecture. While some general understanding about preferred architectures exist in academia, the direct impact on profits is less understood. Due to the defying problem, hybrid approaches considering both financial as well as engineering aspects of architectures are typically based on simplified example models (Jiao, 2012). The desired effect of a structural change can be explained more formally with the in step four displayed graphic. If performed successfully, a structural improvement of an architecture helps to reduce the inclination of the cost curve in a non-linear manner, thereby reducing the impact a general increase in complexity has on cost  $C$  (from  $C_1$  to  $C_2$ ). The related profit function  $P$  is therefore modified towards a new more favourable frontier (from  $P_1$  to  $P_2$ ). This improvement results in smaller periodic complexity and therefore in a system which is more robust to demand fluctuations. Finally it should be noted that while each of the discussed phases can be seen as independent and coherent activities, if conducted in combination, the positive effect may be amplified. For instance, if phase three is performed independently, some complexity cost are likely to remain (see Section 1.1.2.1). On the other hand, a reduction of unprofitable product variety followed by a structural improvement may lead to achieving the initial optimum complexity level. Moreover, the system variability influences how strongly the design range moves away from the system range thus effects how often the four complexity management phases are to be performed.

### 3.5.2 Managing product architectures with visual analytics

Visual analytics is a promising sub discipline of information visualization, which focusses on the consolidation, and interpretation of large data sets through interactive graphs and data mining techniques (Andrienko and Andrienko, 2012). The idea of related tools is to provide the integration of several visualization methods (like the ones discussed in Section 3.4) that would enable an representing relationships in an explicit manner. Different size and colour coding may help to reduce redundancy of the models, thereby indicating the importance and hierarchy of elements and relationships, or particular element type (e.g. part, kind, attribute) (Dork et al., 2011). Liu et al. (2013) propose a six step approach for the interaction with data through visual analytic tools. The steps will in the following be briefly introduced and described in the context of this research. *Step 1* deals with the interpretation of the task and forming the intention for a particular investigation. Dealing with large amount of data in form of generic model for architectures requires the user to be able to understand the insight that is being asked, so that an intention to search for particular areas within the model can be formulated. In *Step 2*, appropriate visualizations are to be simulated. The intention is to mentally describe of possible ways to visually represent the desired insight. This could be to visualize only parts of the architecture model and to collapse



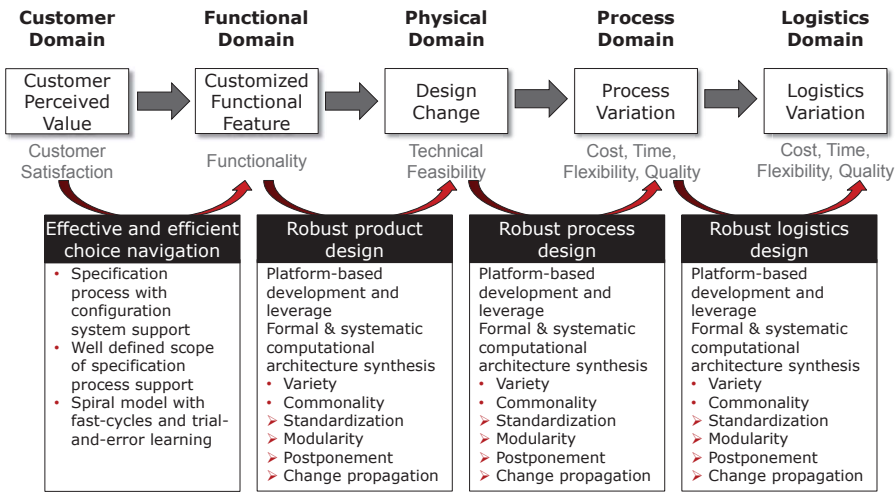
the less interesting aspects. Moreover, to show patterns on a larger scale, it may be better to use generic matrixes, instead of a PVM. In *Step 3*, relevant data dimensions are to be selected. For example, bar charts may be used to represent attribute values relative to each other. *Step 4* includes the use of operations helpful to represent the desired effect. Such operations may include clustering algorithms to form patterns for architecture modules. *Step 5* comprises the actual execution of the operation, where identification of similarities and patterns can be investigated (von Landesberger et al., 2013). *Step 6* finally deals with the interpretation of the visualization. If for example a clustering algorithm was performed, one can now interpret if this process was helpful to identify potential modules (Liu et al., 2013). Hoferlin et al. (2013) introduce additional guideline for the extraction, filtering and manipulation of the underlying data (Hoferlin et al., 2013). The described methods offer a number of useful strategies when working with large architecture, such as with ETO architectures. Moreover, the evaluation of detailed techniques may provide guidance for a tool support development.

### 3.6 Defining general capabilities for MC

Having provided an exhaustive investigation of literature relevant to specification process development and architecture design, now the definition of general MC capabilities can be addressed. As literature on MC and architecture design demonstrates, with the growing intention in implementing MC, companies have to accept major changes within their organization. Since customization shapes the entire product realization process, many aspects along the value chain of a product realization have to be redefined. The consideration of the in Section 2.1.2 aforementioned capabilities aims at assisting this transition process. From an ETO perspective, this includes the establishment of an efficient and effective specification process combined with the design of suitable architectures. A definition on such general capabilities should primarily consider the entire system, as characterized by the customization domains and provide explanation on how customization of a product preferably propagates throughout the system architecture. Figure 3-10 below proposes a such a definition of capabilities based on approaches provided by (Blecker and Abdelkafi, 2006; Cooper and Edgett, 2008; Haug et al., 2012; Hirsch, 2002; Jiao and Tseng, 2004; Meyer and Lehnerd, 1997; Salvador et al., 2009; Wikner and Rudberg, 2005; Zhang and Tseng, 2007). The initial terms of choice navigation and robust process design can readily be combined with the before mentioned discussion on redesigning and assisting of the specification processes. An effective and efficient choice navigation describes the capability to establish a specification process, which is adequately assisted by a CS. The term adequately refers to three characteristics:

1. The *interaction* between user (internal or external) and the CS has to be organized in an effective way, i.e. it fulfills the particular requirements of use, such as visualization (dynamic or static), functionality, integration to other systems, information detailing, feedback on reasoning, sequence of questions, default settings etc.
2. The *scope* of the implanted CS is based on a systematic plan, which supports meeting the desired scale and depth of the specification system support (see impact model in Section 1.3.4).
3. The *implementation* plan is organized stepwise, following the spiral model, focusing on essential functionality first and gradually extending it.

Solution space development on the other hand is extended with the now established understanding of architectures. Instead, with respect to robust process design, modelled after Taguchi et al. (1999), the term robust design is further used for the remaining domains of the system (Taguchi et al., 1999).



**Figure 3-10: Mass customization domains and capabilities**

From an architecture perspective, robust design integrates the concept of a platform based product development with the described solution space development. In this context, the aim of a robust design is to use a platform strategy, which makes it possible to become resistant to changes of external and hence uncontrollable factors (noise) (Simpson, 1998). When minimizing the performance variability caused by the noise factors, a stable mean performance of the product can be achieved (Chen et al., 1997). In the context of this research, noise can be understood as the variability in operational performance. Eventually this means to reduce the impact of external complexity (see Section 3.5.1), thereby achieving a stable “near mass production” performance. In this way, a robust system is described from a pure architecture modelling perspective and should not be confounded with specific methods for quality management in mechanical design as e.g. discussed by Hasenkamp et al. (2007) (Hasenkamp et al., 2007). Next, the objective of establishing and leveraging platforms can be merged with the previously described need for a formal computational architecture synthesis. As elaborated in Section 3.1.1, a formal and systematic (from analysis model to computer model) synthesis supports the process of decision making towards preferred architectures for customization, which balances the right level of commonality and variety, through standardization, modularity and postponement. Eventually, the ability to describe how changes propagate throughout the system helps to align the architecture design. According to this theoretical investigation, companies which manage to transact to a large extend all capabilities are likely to become more successful mass customizers.

Thereby, this section has answered the research question *RQ1.1*.

**RQ1.1:** What general capabilities should ETO companies develop when implementing mass customization?



### 3.7 Chapter summary

Chapter 3 presented a state-of-the art understanding of a system design suitable for MC. The subject was discussed within the context of architecture development and management, where initially preferred architectures for MC were defined. Next, the architecture design process was elaborated and requirements for a formal synthesis method were discussed as a basis for and improved decision making. Eventually, different modelling methods for single products and entire produce families were assessed according to the requirements. An



extended modelling was introduced, to better meet the requirements. The gained insight helped to develop a constant framework for the management of complex architectures. Different visualization and analytical techniques were included, to address the need for consolidating and interpreting large data sets from architectures. The chapter was completed with the definition of general MC capabilities, which consider the now created understanding of operational and architectural aspects of the subject, thereby answering *RQ1.1*.

# 4 MASS CUSTOMIZATION IN ENGINEER-TO-ORDER INDUSTRIES

The findings from chapter 2 and 3 clarified that both that the operational handling of customization as well as the actual architecture design and management are crucial for enabling MC in ETO industries. The results from both chapters determined the expansion of theoretical review into themes of particular interest. The literature investigation was comprehended with empirical investigation, to obtain a more thorough understanding of the corresponding subjects. This chapter provides an consolidated description of the obtained results organized in six sections. Section 4.1 presents an overview over the published research results. Section 4.2 to 4.5 discuss the individual publications structured according to the main scope of the investigated MC capabilities and the related research questions. Finally, Section 4.6 concludes with a reference framework referring the main outcome of the chapter. The framework is based on the combined insights from the theoretical and empirical studies and reflects upon the successively described publications.

## 4.1 Publication overview

In this section an overview of the achieved results in form of the developed publications is provided. The papers are listed in the order of the addressed research questions and further state the utilized method as described in Section 1.3.2.

No.	Publication	Method
A)	Bonev, M., and Hvam, L. (2002), "Analyzing the Accuracy of Calculations When Scoping Product Configuration Projects", <i>Lecture Notes in Artificial Intelligence</i> , Vol. 7661, pp. 347–358.	#2
B)	Bonev, M., and Hvam, L. (2013), "Performance measures for mass customization strategies in an ETO environment", <i>Proceedings of the 20th EurOMA Conference</i> . European Operations Management Association.	#2, #4, #5
C)	Bonev, M., and Hvam, L. (2012), "Knowledge-based geometric modeling in construction", <i>Proceedings of NordDesign Conference 2012</i> . Aalborg University, Center for Industrial Production.	#1
D)	Bonev, M., Korell, M., and Hvam, L. (2013), "New complex product introduction by means of product configuration", <i>Proceedings of the 15th International Configuration Workshop</i> , August 29-30, Vienna.	#7
E)	Shafiee, S.; Hvam, L.; and Bonev, M. (2015), "Scoping a product configuration project for engineer-to-order companies", <i>International Journal of Industrial Engineering and Management (IJIEIM)</i> , p. 207-220. Earlier version originally published in: <i>Proceedings of 6th International Conference on mass Customization and Personalization in Central Europe (MCP-CE 2014)</i> , University of Novi Sad.	#11

- F) Hvam, L.; Bonev, M.; Haug, A.; and Mortensen, N.H. (2014), "The Use of Modelling Methods for Product Configuration in Industrial Applications", *Proceedings of the 7th World Conference on Mass Customization, Personalization, and Co-Creation (MCPC 2014)*. In Brunoe, T.D., *Lecture Notes in Production Engineering*. pp. 529-539, Springer, 2014. S1
- G) Bonev, M., Wörösch, M., and Hvam, L. (2015), "Utilizing Platforms in Industrialized Construction: A Case Study of a Precast Manufacturer", *Construction Innovation*, Vol. 15 No. 1, pp. 84-106. #8
- H) Wörösch, M.; Bonev, M.; and Mortensen, N. H. (2013), "Product platform considerations on a project that develops sustainable low-cost housing for townships", *CIB World Building Congress 2013*, Brisbane, Australia. #3
- I) Bonev, M.; Wörösch, M.; Hauksdóttir, D.; and Hvam, L. (2013), "Extending product modelling methods for integrated product development", *Proceedings of the 19th International Conference on Engineering Design (ICED13): Design For Harmonies*, Vol. 4 Design Society, p. 219-228. #6
- J) Bonev, M., and Hvam, L., "Supporting the design and mass customization of product family architectures using computational structural analysis methods", *In journal review*. #10
- K) Myrodia, A.; Bonev, M.; and Hvam, L. (2014), "Managing complexity of product mix and production flow in configure-to-order production systems", *Proceedings of 21st EurOMA Conference: Operations Management in an Innovation Economy*. European Operations Management Association. #9

## 4.2 Assessment of MC capabilities

This section investigates possibilities for the assessment of the in Section 3.6 refined MC capabilities. It addresses the first research question (RQ1: How can the transition process of ETO companies moving towards MC be supported effectively?) by elaborating on methods for evaluation and complementing them with a case study.

### 4.2.1 Paper A: Initial quality assessment

**Title:** **Analyzing the accuracy of calculations when scoping product configuration projects**

Published in: Lecture Notes in Artificial Intelligence, Vol. 7661, 2012, p. 347–358

Case studies: #2

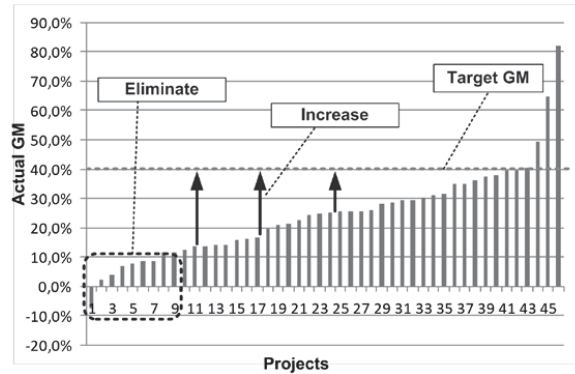
#### 4.2.1.1 Research objective and research question

Drawing upon the understanding of MC capabilities, this first paper is an initial intent to answering research question *RQ1.2* (How can the quality of such general MC capabilities be assessed and their development be further directed?). The case study was based on a leading producer of precast concrete elements for buildings, where customized products are offered for various building types, e.g. industrial buildings and warehouses or apartments and offices. Being successful on the market for many years, the company has gained a lot of expertise and working know-how. But because of the changing requirements in the construction business, the company is asked to respond to this dynamic situation efficiently. The manufacturer is intending to redesign its product portfolio and the way it is doing business. However, like in most companies within this industry, product development and development of business processes have been planned separately. This is especially common for the construction industry, which is regarded as being a project-based business sector (Scherer and Sharmak, 2011). This product development is typically organized in projects, where the individual products are being developed with a rather random reuse of previous solutions and knowledge. Consistent with the findings from Section 2.2.4, this unstructured reuse of knowledge resulted in high variability in operational performance. The scope was therefore to investigate the cause of this variability, thereby identifying ways to reduce it.

#### 4.2.1.2 Research contribution

##### ***Quantifying the accuracy in cost calculation***

When investigating how successful company delivered custom tailored products, an idea was to study the parameters that assess this performance. From a financial perspective, the so called Key Performance Indicators (KPIs) aim to summarize the ultimate results of a business, which may consist of a revenue ratio, gross margin variability or deviation, Earning Before Interests and Taxes (EBIT) and profitability (Balatbat et al., 2010; Nudurupati et al., 2007). Experiences from collaborations with other companies making complex customized products have proved the majority encounter this significant gross margin variability. Figure 4-1 below shows one of the industrial examples, a manufacturer providing customized building equipment, where the actual gross margins (GMs) of completed projects vary between -60% to +50%. The achieved GMs of individual projects have been sorted according to their success, assuming that projects with higher GM would be regarded as more successful.



**Figure 4-1: Gross margin deviation for engineering intensive projects**  
Source: Adapted from (Mortensen et al., 2010)

Even though the manufacturer has estimated a 20% margin for calculating all his quotations, the post calculation reveals a very different picture of the obtained GM. No doubt, there might be many reasons why companies are experiencing such a significant variation. But assuming that a relatively fixed GM ( $20 \pm 5\%$ ) is pre-estimated, in general, it can be concluded that unexpected variations on actual GMs result from poorly made pre-estimations on costs for making specifications, manufacturing and for providing services. As indicated in Figure 4-1, at this point proposition was that more accurate pre-calculations help companies to decide on their product portfolio and accordingly to evaluate beforehand which projects are profitable. Better performed estimations would thereby help to improve the quality of specifications and products by means of an improved conformance of the requirements (Trentin et al., 2012).

#### ***Assessing the specification process in ETO companies***

Besides the well described studies on analysing lead time performances, recourse utilization etc., a framework is introduced where the less discussed issue of strongly varying pre and cost calculations is further investigated. The framework is based on the discussed procedure from Section 2.2. As Figure 4-2 displays, to evaluate how successful completed projects were and to what percentage the manufacturing costs were affecting these results, the analysis of GMs and the distribution of manufacturing costs is suggested. In case the KPIs fluctuate stronger than the company's business strategy allows, in the third step, traditionally one or more TOBE specification processes are to be drawn. With the focus on cost calculations, a TO-BE calculation processes is proposed and a subsequent business case, where the most suitable scenario is chosen (step 4). Finally, in step 5, a plan of action is to be created ensuring the continuation of the project. Having briefly described the proposed framework, in the following an analysis method has been applied.

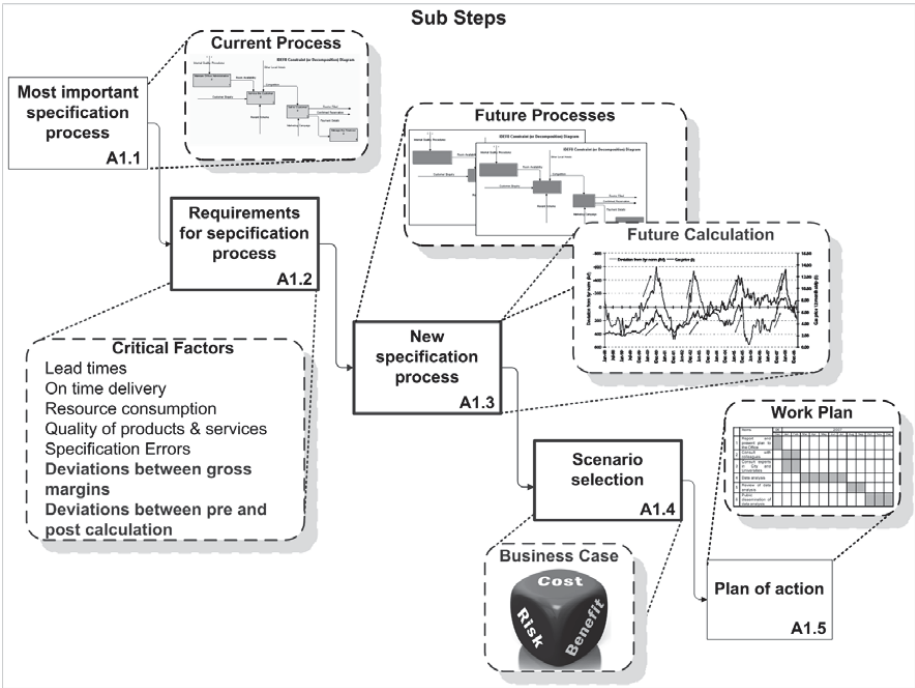


Figure 4-2: Development of specification processes

*Investigating the current specification process*

To improve the operational performance, the precast manufacturer is considering the use of IT tools, such as CSs. In order to facilitate the success of the planned configuration project, a clear defined scope has to be developed. Thus, following the procedure introduced above, in the beginning, the most important specification processes have been studied.

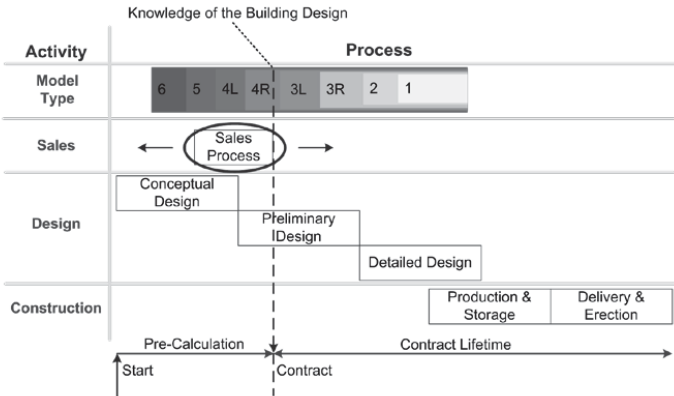


Figure 4-3: Main activities in the precast industry

Figure 4-3 illustrates a high level representation of major procedures in the precast industry, where in addition to the actual design process, common management practices have been established to create “Models” of the same basic processes across the enterprises (Sacks et al., 2004). The contract between a contractor and the precast manufacturer is

made on the basis of these models (Bips, 2012). They determine to what extent the manufacturer is involved in the design process of the building. In “Model 6” for instance, the manufacturer is supporting the design process from the very first beginning, making structural analysis for the entire building based on a given design intent from the architects. In contrast, in “Model 1”, the foregoing design activities are done by the collaborating partners, while the precast manufacturer is focusing only on the detailed design for the concrete elements, including the reinforcement and installations.

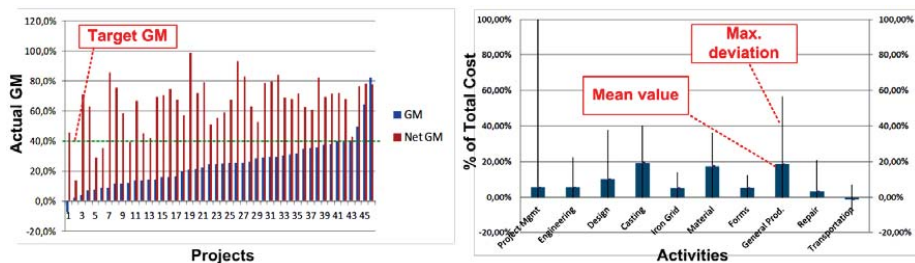
### **Analyzing deviations between gross margins and pre- and post-calculations**

Regardless of the model type, the precast manufacturer and his client typically agree on a contract at a point of time where the preliminary or even conceptual design of a building is still made. The sales department is using its experience to pre-estimate the amount and type of concrete elements that are needed to construct the designed building. Based on their pre-estimations, the price for delivering the required precast elements is negotiated. Because of the complexity of construction projects (van der Aalst et al., 2003), estimating the correct sales price is challenging. In case the price is set too high, the precast manufacturer will not be able to compete on the market. On the other hand, if the sales department is offering a too low sales price, the profit will be reduced or the company might even produce with loss. In sum, because at this stage no detailed design information is available, uncertainty and high risk for changes on the design hamper making accurate cost estimations.

Apparently, the sales process in the precast industry is rather complex, as each project requires different products and most of the decisions are made at a point of time, where only little knowledge about the final building design is available and uncertainties about upcoming changes are present. This leads to the obvious assumption that the pre-estimated prices are often not representing the actual costs, or in other words there is a high variability between pre- and post-calculations. The results from the qualitative analysis are verified through a quantitative data analysis, leading to the question: how could the company benefit from implementing a CS in support of the sales process?

### **Identifying the major benefits from using configuration systems**

To verify the evidence from the qualitative oriented analysis, a nearly complete sample of projects performed over a period of 2 years were investigated. Since the objective was to identify how good or bad the accuracy of the cost estimation is, the two proposed indicators of variability in GMs and pre- vs. post calculations (dependent variables) were set in relation to possible cause (independent variables), e.g. the project size.



**Figure 4-4: Deviation between gross margin and pre- and cost calculation**

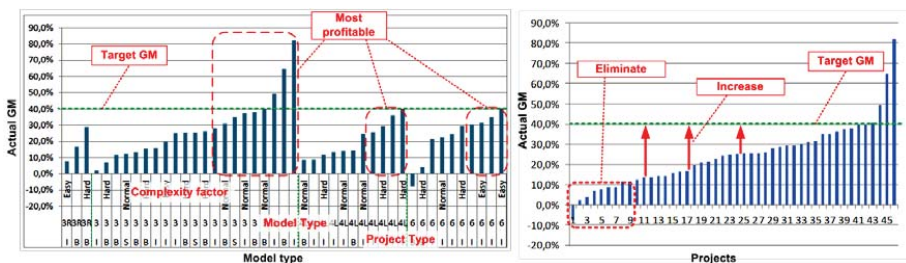
As displayed in Figure 4-4, the projects' GMs and the relative allocation of the costs compared to the total cost were evaluated. To obtain a clear cost picture for each project, only direct and indirect variable costs were considered, leaving out fixed costs, e.g. for administration, and overheads. The graph to the left compares the total GMs with those when the

material costs are excluded (Net GM). The deviation shows that the labour cost do not behave proportional to the project size, as the GM and the one without the material costs do not change correspondingly.

The graph to the right illustrates the strong deviation of the relative activity cost. Here, the pre-work (project management, engineering, design) is not equally distributed across the sizes, but is significantly higher for smaller projects. Also the relative costs for production (casting, reinforcement, forms and material) highly vary with the project size and have the highest percentage for mid-range projects (not in the graph). In sum, the analysis shows a surprisingly high variation of actual GMs and relative cost deviations, where the labour cost is not proportional to the produced elements. Assuming well-functioning manufacturing process, the result indicates that the current pre estimation of both sales prices and labour resources is not being done sufficiently.

### *Contribution to future specification process and cost-benefit analysis*

When designing the TO-BE specification process, the pattern for the deviations has to be revealed. To identify the cause-effect relationship for the strongly varying indicators from the first analysis, the domain experts were asked to provide additional information to the projects and the way they can be compared. Hence, apart from the project sizes, it was decided to consider an estimated complexity factor (based on the produced elements), the model type and the project type, e.g. apartments or malls.



### Figure 4-5: Analytical results and cost-benefit investigation

The left graph in Figure 4-5 illustrates the deviation of the GM in relation to the most influencing factor, the model type. The analysis shows that the actual GM is much lower (24%) than the one the company is aiming for. Besides, it becomes clear that the company is most profitable for a certain combination of model type, complexity factor and project type. For these types of projects, the actual GMs were higher and the done pre calculations were more accurate.

Once all influencing factors have been detected, a more precise price calculation model that better reflects the actual cost picture can be designed and incorporated in a CS. The right graph in Figure 4-5 indicates the scope for decision-making, when deciding on a scenario for the right calculation method. Here, the company has to determine: 1. what would be the minimum GM, which would cover the fixed costs and overheads, and 2. how much could the company benefit from a more accurate price calculation. Indeed, the proposition is that a sufficient calculation model leads to a stronger negotiating position with the customer and thus helps to increase the GM towards the targeted one. Therefore, more precisely, depending on the company's strategy, it is argued that the following possible scenarios shown in Table 4-1 below might be feasible for the introduced case.

### Table 4-1: Cost-benefit analysis



	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Description	Keep current status	Remove all <10% GM	Remove all <5% GM, increase 5-10% by 5%	Remove all <5% GM, increase 5-10% by 10%	Remove all <5% GM, increase 5-30% by 5%
Turnover	280	247	275	277	285
Gross Margin	24%	28%	26%	27%	27%
Fixed costs and overheads	39	34	38	39	40
EBIT	28	35	33	36	37
EBIT in %	10%	14%	12%	13%	13%

To ensure anonymity, the total numbers have been changed in the table, whereas their relative ratios have been kept accordingly. A common EBIT of 10% can be assumed for the precast sector (Balatbat et al., 2010). This number has been used for the baseline *Scenario 1*, which further serves as the comparison measurement. Then, in *Scenario 2 to 5*, different combinations of rejected projects with a simultaneous increase of the remaining GMs are proposed. As expected, in the current case, “Scenario 5” appears to be most profitable for the company, where all projects with less than 5% GMs are rejected, but instead the GM for the remaining projects with 5-30% GMs is increased by 5%. However, depending on the market situation, “Scenario 2” or “Scenario 4” might be easier to realize. In these cases, the company would obtain a slightly smaller turnover, but which at the end is overcompensated by the increased GMs and reduced costs, resulting in an increased EBIT.

#### 4.2.1.3 Conclusion

The increasing implementation of product configurators over the last two decades has proven a number of potential benefits for companies providing customized goods. However, in academia and practice only little analytical methods have been used to actually uncover these benefits and thus to utilize the maximum capability of the supportive CSs. The framework presented in this paper reveals an evident opportunity for better scoping planned configuration projects and thereby to lowering the risk of abandoning projects. To this end, a less discussed investigation of variability between gross margins and pre- and post-calculations have been applied on an industry case, an ETO manufacturer providing building products. The analyses confirmed how a well-structured quantified approach, supported by a cost-benefit analysis, can determine the potential advantage of more accurate cost and price calculations and thus lead to improved sale processes. In order to keep the risk of abandoning (see Section 2.2.4) a planned or even initiated project down, ETO companies may focus on identifying the highest potential and eventually the most benefits from using CSs. CSs can be used to create an accurate estimation of prices for a building project and therefore reduce the variability in performance. In the context of the research question, this paper investigated empirically how reducing the variability of operational performance may help to increase the capability of an efficient and effective choice navigation, which eventually requires creating a more robust system design. Another insight concerns the reduction of unprofitable building projects, as a way to reduce the time-dependent complexity of the system (see Section 3.5.1.3).

## 4.2.2 Paper B: Model revision and cross-case analysis

**Title:** **Performance measures for mass customization strategies in an ETO environment**

**Published in:** Proceedings of 4th Production and Operations Management World Conference, 2 - 4 July, 2012, Amsterdam

**Case studies:** #2, #4, #5

### 4.2.2.1 Research objective and research question

The experiences from *Paper A* suggested that investigating the variability of operational performance in general may reveal a broader potential for ETO companies to work on improving the quality of their MC capabilities. The emphasis of second study was therefore develop a systematic valuation method which initially assesses the occurring variability. Once successfully completed, such a performance analysis should be capable of specifying how the previously defined objectives towards the development of MC capabilities are to be achieved. Based on a literature study, the paper elaborates further on the identified aspect of varying margins. Eventually, a framework is introduced that strives to better meet the requirements for the intended assessment. The framework is finally tested on three industrial case studies. Since full access to detailed data within each company was given, validity of the research findings can be created through an in-depth investigation. To enable a comparison across the studies and thus to achieve external validity (Yin, 2003), each case study preferably follows the same performance measurement approach. Rigor of data collection is insured through foregoing qualitative methods (e.g. unstructured and semi-structured interviews). Subsequently, quantitative data is collected and analyzed by means of the proposed methodology.

### 4.2.2.2 Research contribution

#### ***The performance variability assessment method***

A widely used approach for assessing the financial and operational status of a company and monitoring its development over time is to introduce relevant performance measures (Kaydos, 2000). Such measures can be seen as a metric for quantifying the efficiency and effectiveness of an action, where performance measurement describes the process of quantification (Neely et al., 2005). In principle, in order to evaluate how successful firms are with their MC strategies, the various domains of customization have to be investigated (Mortensen et al., 2010). As recognized in *Paper A*, while measuring the operational performance, e.g. cost and lead times, is rather common in the MC domain (Su et al., 2005), the financial impact of customization has less been discussed (Duray, 2006; Forza et al., 2008). Alternatively, including both aspects of operations management into a comprehensive measurement metrics could result in a tremendous task that is impossible to be handled (Melnik et al., 2004). Since such a metrics could then easily contain an unreasonable large number of key indicators (Kaydos, 2000), conducting the analysis would take an unreasonable amount of time and one would very likely lose focus on the most critical performance aspects.

In a case study, Mortensen et al. (2010) point out that especially manufacturers offering ETO products often struggle with significant contribution margin (CM) deviations. Correspondingly a considerable high amount of their portfolio generates no or little profit. From an MC perspective, such deviations in margins should come as a great surprise. According to the discussed theory, developing MC capabilities requires a clear understanding and coordination of the relationships between markets, products and processes and the supportive logistics. Companies which align their effort would even in a fast changing environment be able to obtain a more stable operational performance. Assuming that for similar products

relatively constant CMs are pre-estimated, such unexpected deviations may result from poorly made cost pre-calculations of costs and market prices. To obtain a complete performance analysis, the comparison of planned vs. realized calculations can for poorly performing products be accordingly applied to other operational dimensions, such as for time and quality. In result, for ETO companies moving towards MC, unexpected performance deviations could uncover possible weaknesses of their activities and potentially focus the need for further action. A reasonable assumption is therefore that investigating deviations between CMs and between pre- and post-calculations of the operational performance reveal potential vulnerabilities of ETO manufacturers moving towards MC, where high deviations between CMs within a product family; and high deviations between pre- and post- calculations of the related operations; indicate that MC strategies are not aligned.

The analysis of variability is suggested to be performed in the following four major phases. Table 4-2 provides an overview over the phases and the related activities of the framework. As a starting point, in Phase 1 the boundaries for analysis can be set by focusing on a limited number of product families and corresponding projects in a defined period of time. In accordance with research studies and current business practices, initially the main characteristics of the product family are categorized from an external perspective, where market segments, customers and key product features are identified (Kaplan, 2012; Mortensen et al., 2010). To obtain an overview over the stated project performances, in Phase 2 pre-calculations regarding turnover and the related distribution of costs are collected. Marginal (contribution) costing is then used to provide a more realistic picture about how the turnover is distributed throughout the projects. Since only pre-calculated variable costs are considered, loading incorrect overheads onto products can be avoided (Kloock and Schiller, 1997). To achieve further insight, turnover and CMs are related to the identified market segments, customers, product features (Scheiter et al., 2009). The combination of certain aspects therein potentially indicates patterns and cause-effect relationships of the project performance. In addition to cost related measurements, for critical projects planned lead times, promised quality and desired flexibility of processes can be investigated (Neely et al., 2005). However, as in praxis for ETO manufacturers some of the information might not be formally available, in some cases it is useful to additionally conduct a qualitative assessment of the aspects. Interviews with responsible managers may give indication on what measures to focus on at the first place.

Since until then the performance analysis is solely based on the pre-calculated figures, in the following steps post-calculations are applied to validate these results. Activity-based costing (ABC) is used to determine the main cost drivers for each project (Cooper and Kaplan, 1988). As most typical activities in manufacturing firms involve by definition manufacturing, sales and procurement processes, for the comparison of the results with the foregoing analysis only labour and material recourses are taken into account. Therefore not directly related resources e.g. for administration are not further considered. In case additional operational measures, e.g. lead times, are found to be critical performance factors, they should as well be included in the post-calculation analysis. By comparing deviations between the planned and realized figures, e.g. promised vs. realized delivery time, additional potential drawbacks can be revealed. At the end of Phase 2, major findings are to be summarized and recommendations for further action are to be set. In order to confirm the results and to achieve data triangulation, a subsequent qualitative analysis (Phase 3) is performed. Interviews with the responsible staff help to identify the rationale behind the results and to either verify or falsify the conclusions. In case the hereby gained insight indicates the need for a revised investigation, a more detailed quantitative analysis can be conducted. The last step of the analysis (Phase 4) involves a plan of action, where major activities for further action are to be defined according to how successful the capabilities of MC have yet been accomplished

**Table 4-2: Framework for performance variability assessment**

Phase 1	Phase 2	Phase 3	Phase 4
Scope of Analysis	Quantitative Analysis	Qualitative Analysis	Action Plan
1.Choose product family (focus on finished goods and components)	1.Clarify business strategy for EBITs and CMs	1.Present findings from quantitative analysis	1.Evaluate product family based on major deviations
2.Define market segments and main customers	2.Calculate turnover for market segments, customers and product features	2.Discuss possible cause-effect relationships	2.Prioritize weak points
3.Define product features	3.Calculate estimated CMs for market segments, customers and product features	3.Conduct further quantitative analysis	3.Focus transition activities on major weak points
4.Identify data sources (responsible staff and IT systems) for case period	4.Use ABC to calculate actual CMs for market segments, customers and product features	4.Refine findings and establish conclusions	4.Follow up transition progress
	5.Extend analysis for products with high deviations in CMs and pre- vs. cost calculations		
	6.Summarize major findings and set initial goals for further action		

### ***Applications and evaluation of the assessment framework***

To provide empirical evidence for the chosen analysis methods, the proposed conceptual framework was applied on the three cases studies #2, #4 and #5. Testing the framework on companies which substantially differ in size, industry and product range helped to better understand it's the practical difficulties and limitations. However, it also became more challenging to use a consistent analysis approach throughout the case studies. One of these challenges is the availability of data in each of the case studies. For instance, while for company #5 on a high level enough information regarding pre- and post-calculated prices and cost was available, for company #2 and #4 big part of the data was not documented at all. Nevertheless, to enable the analysis, for the latter cases already at the beginning of the analysis in Phase 1, additional interviews with managers and engineers from in different department had to be conducted. Especially for the pre-calculation related to prices and costs, often much of the information depended on the knowledge of experienced individuals, which was neither documented nor formally described. Therefore, as indicated in results in Table 3, for some measure only qualitative estimations could be obtained. This resulted in pre-calculations which later often turned out be rather unrealistic.

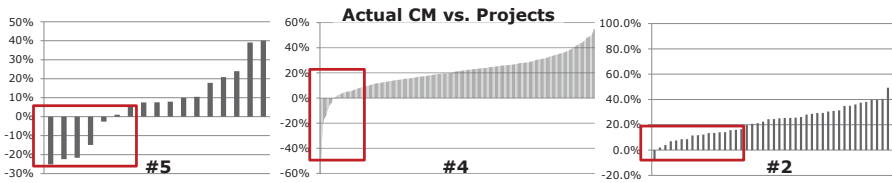
On the other hand, a smaller company size proved to be beneficial for investigating post-calculations. Data concerning main cost drivers of projects could easier be investigated, while interviews with the responsible managers helped to identify other operational aspects within the organization. For company #5 the situation was quite different. Having initially analyzed the project performance on an aggregate level, investigating further details concerning the interesting aspects of the analysis turned out to be surprisingly difficult. Data was mainly available on an aggregate level and in additional, individuals had a less clear understanding of possible cause-effect relationships with regards to the chosen metric.

**Table 4-3: Abstract of key figures of the cases companies**

Case		#5	#4	#2
General Information	Industry	Oil & Gas	Industrial & Manufacturing Security	Construction
	Turnover [in Mil. €]/ Employees	6000 / 20.000	100 / 600	50 / 250
Phase 1	Unit of Analysis	1 Product Family	2 Product Families	Product Portfolio
	Sample Size	12	550	80
Phase 2	Turnover [in k. €]/Project	50	20	1000
	Contribution Margin (planned)	Mean: 21% STDEV: 11%	Mean: 25% STDEV: 3%	Mean: 40% STDEV: 5%
Phase 3	Contribution Margin (actual)	Mean: 8% STDEV: 18%	Mean: 21% STDEV: 6%	Mean: 24,7% STDEV: 16,5%
	Main Cost Drivers & Deviations	Production (60%±5% ) Engineering (13%±5%)	Commissioning (20%± 10%) Project Man. (15%± 10%)	Production (45% ± 13%) Material (20±25%)
Phase 3-4	Main Findings	50% of the EBIT decrease cannot be explained	High deviation in estimated and actual prices	High deviation in project management and engineering
		Too much resources for repetitive Engineering tasks	Unprofitable market segments	High deviation in estimated and actual prices
Phase 4	Action Plan	Assortment matching	Assortment matching	Assortment matching
		Product standardization	Solution space development	Flexible automation
Phase 5	Action Plan	Process standardization	Process standardization	
		Variant derivation	Variant derivation	

### Summarizing the results

Table 4-3 provides an overview of the conducted case studies in relation to the defined phases. Since company #5 works with relatively large projects that involve the delivery of whole systems, to be able to perform the analysis within the limited timeframe, a rather small sample size was chosen. On the other hand, bigger sample sizes were used for smaller and simpler projects in company #2 and #4. A general outcome of the analysis for all three case studies is that the planned CM performance of the projects was in average overestimated, while the related standard deviation remained steadily on a lower level. Both figures indicate that for a large number of the projects the case companies continuously plan with inaccurate cost estimations, where for extreme cases negative EBITs were achieved. The realized CMs and post-calculations reveal a less stable picture. In Table 4-9 the results from analysis of the actual CMs across the projects are exemplarily detect. Despite the different characteristics for each case company, in all three cases, a considerable high amount of projects generates low or negative CM. The cause of this poor performance needs a more detailed investigation.



**Figure 4-6: Example of the actual CM analysis for each project across the companies**

As expected, the major cost drivers for the projects in all three companies are costs related to production. Due to the special business of company #4, a big cost factor accounts for the commissioning of their products. The main findings from three case studies show that even though the actual performance of their projects was less than what the companies initially expected, the causes can be different. While company #5 and #4 have inter alia to put more effort in standardizing their processes, company #2 appeared to have rather robust process design. However, due to the lack of automation and little understanding of the planned costs, several other drawbacks could be revealed. Company #4 was advised to re-define on the offered solution space and the target market segments, since in some cases negative EBITs were unintentionally achieved. Finally, in accordance with literature, all of the three case companies could improve the specification process through the implementation of a CS which would create a more accurate estimation on variant profitability.

#### 4.2.2.3 Conclusion

Drawing upon literature, this study extended the initial investigation from *Paper A* and developed a systematic method for the evaluation of capabilities for MC. To conform to the identified objectives for ETO companies, the suggested approach closely investigated deviations between CMs and between pre- and post-calculations of operational measures. The results evaluate how high variability of the chosen performance measures negatively influences the operational performance. Based on the gained findings, recommendations for a further development of the quality of MC capabilities were given. The gained insights supported the understanding for answering the second research question (RQ2: How should the specification process of ETO companies moving towards MC be developed?).

### 4.2.3 Section summary

Section 4.2 has reviewed the literature relevant for the assessment of MC capabilities. It was learned that ETO companies are in particular sensitive to variability in operational performance, causing high uncertainty in the profitability of product variants and thus to projects. The reason for this variability was seen in the in Section 1.1.2.2 described challenges of ETO firms. A way to reduce the variability is to investigate its cause. Therefore, apart from analyzing the mean operational performance, it is likewise important to study where variability occurs. Based on an initial empirical investigation in Section 4.2.1, in Section 4.2.2 a method was developed and tested through a cross-case analysis in three different industries. The method uses the variability of contribution margins within product families to scope a more detailed investigation. Differences in pre- vs. post-calculations were then identified with the help of available reporting systems and own investigations using activity-based costing. As a result, recommendations were given to reduce the occurring variability, potentially leading to a development of the general MC capabilities.

Thereby, this section has answered *RQ1.2*. A concept for an improved understanding for a specification system support will be developed in the next section.

**RQ1.2:** How can the quality of such general MC capabilities be assessed and their development be further directed?



## 4.3 Development of effective and efficient choice navigation

This section addresses the second research question (RQ2: How should the specification process of ETO companies moving towards MC be developed?) by extending the current understanding of the subject through selective literature studies which are further complemented by three case studies in three different companies.

### 4.3.1 Paper C: Initial investigation of specification process support

**Title:** Knowledge-based geometric modeling in construction

**Published in:** Proceedings of NordDesign, 22 - 24 August, 2012, Aalborg

**Case studies:** #1

#### 4.3.1.1 Research objective and research question

Based on the gained insight from *Paper A and Paper B*, this study investigates the actual implementation of CSs in support of the specification process. The objective was to refine the understanding on the three sub questions (RQ2.1-RQ2.3) in a situation where the ETO specification process is to be supported on an established architecture, with no particular adjustment on the product design. The study was therefore framed within the context of knowledge-based engineering (KBE) as way to increase the efficiency of engineering activities. A corresponding empirical investigation was performed within the construction sector.

#### 4.3.1.2 Research contribution

##### ***Research background***

Despite all the research effort that has been done especially with regard to the BIM approach, creating tools to support the construction work is still challenging (Hartmann et al., 2012). Tizani and Mawdesley (2011) thus state that in order to facilitate the progress towards higher productivity throughout the building lifecycle, more aspects have to be considered. For instance, apart from the BIM approach, information modelling should also address operational practices of construction. Furthermore, the authors illustrate that with the detailed digital representation of products and processes will help to improve the accuracy and productivity in construction toward a higher degree of automation. Product and processes should thereby follow standardized modelling technologies (Tizani and Mawdesley, 2011).

Inspired by the industrialization in the plant and machinery industry, the attempt with this research is to bring forward the idea of using IT tools and standardized modelling techniques to facilitate a higher degree of automation of the performed construction activities. The focus in particular set on evaluating the current applications of knowledge-based IT support to improve the efficiency of ETO manufacturers in designing geometry-oriented models. A major objective is hereby to automate recurring and non-creative design tasks and to establish generic product models that enable the representation of complex geometry-oriented product architecture.

##### ***Design activities in the precast industry***

Even though building design activities have been performed for hundreds of years, it wasn't until 1960s when the design process was initially formalized (Archer, 1968). Further descriptions of processes and practices have followed since, aiming to define the activities of the involved stakeholders in detail. The main activities were structured according to the lifecycle of a building, where five major phases were identified: feasibility study, design, construction, operation and support, and demolition (Eastman, 1999). Going into detail, the



design phase thereby contains a conceptual, preliminary and detailed design, clearly separating the design processes from the construction operations (Al-Masalha and Wakefield, 2000). Similar to the design approach in other industries, a preferred design approach in construction is the top-down design (Myung and Han, 2001), where first the overall product, i.e. the building, is defined, followed by breaking it down into subsystems, assemblies and physical components (Mora et al., 2008). Based on the initial design intent of the architect, engineers are transferring a design concept into a structural model with the objective to create feasible structural solutions while referring to given architectural patterns and constraints. Such decisions are mostly based on the engineer's knowledge and experience of the realization of the design intents on a given situation. In the detailed design phase further specifications determining the precast elements need to be done to define the structure and assembly layout, the assembly design and analysis and the piece and connection detailing (Sacks et al., 2004). As most of the building parameters have already been decided, now, concrete calculations of the costs for production can be made. With the focus on specifying the reinforcement, the dimensions and surfaces, and the exact placement of recesses for doors, windows and other installations for each precast element, the design procedure is recurring in nature.

### ***Managing knowledge in the design process using knowledge-based engineering for repetitive design tasks***

A number of research has been done to investigate how to reduce the resources spent for routine design. KBE has thereby been identified as a major approach to study the reuse of product and process knowledge with the aim to reduce the time and cost spent on product development thorough automation of repetitive design tasks (Verhagen et al., 2012). Depending on the application, various definitions on KBE can be found in literature. Stokes (2001) refers to KBE as the assignment of advanced software techniques to capture and reuse product and process knowledge in an integrated way (Stokes, 2001). According to Chapman and Pinfold (2001), KBE is an *"engineering method that represents a merging of object oriented programming (OOP), artificial intelligence (AI) techniques and computer-aided design technologies, giving benefit to customized or variant design automation solutions"* (Chapman and Pinfold, 2001). To realize the required integrity, the knowledge to be modelled should therefore be provided within the CAD systems that are used by engineers and architects. Geometrical constraints and heuristic knowledge on the product design can thereby be stored in the so called knowledge base (Myung and Han, 2001). Sandberg et al. (2011) further state that by using rule-based applications, geometrical models can be represented in a way which is beyond the traditional parametric models. For routine engineering tasks such applications are found being useful (Sandberg et al., 2011). The authors explain how object-oriented KBE software makes use of predefined classes for major geometry objects, such as blocks and cylinders, and predefined functions for modelling parameters, like *min* or *max* functions. Application Programming Interfaces (API) and Macros help to create design and analysis loops, which after a number of iterations can eventually lead to the optimal overall design. As the authors focus on supporting an early stage of the design process, the detailed design is suggested to be carried out in the CAD models, once a suitable product design containing the desired overall parameters has been achieved.

One of the first attempts to implement rule-based design in construction was done by Gross (1996). The author refers to a constraint-based program for developing suitable construction kits. Similar to building up a house out of LEGO blocks, the program defines rules for the dimensions and the positioning of building components, which eventually leads to nearly unlimited possibilities of approved combinations (Gross, 1996). A similar approach is suggested by Sandberg et al. (2008), where a CS is used to define the dimensions and placement of stairs within a building. The program provides support to the sales and design process by implementing if-then-else rules for choosing the right stair geometry for a given layout and calculating the production costs. To achieve better product documentation and to obtain information on geometry configuration and engineering knowledge, the authors

suggest the use of a product data management together with the stair configuration. Even though not further specified, the integration to various CAD systems should be solved through a connection with the API of the systems (Sandberg et al., 2008). A recent study on KBE in the precast industry by Jensen et al. (2012) refers to a rule-based support through the use of a CS which is directly integrated into a CAD system. SolidWorks (Dassault Systèmes, 2012) is chosen as a main CAD system for both, making parametric product models and for realizing the communication with product data management (PDM) systems. A standard integration with the CS TactonWorks (Tacton Systems, 2014) creates the desired design configuration of the dimensions and exports an xml-based parametric file to widely applied architectural CAD software, such as Autodesk Revit (Autodesk Inc., 2013). The engineer using this software can then import all precast components and continue the design process manually. Depending on the application area, the communication of the product to the different stakeholders, such as production, engineering and sales, is provided through CAD drawings and lists of rules for dimensioning (Jensen et al., 2012).

The studies described above demonstrate the potential the approach of using KBE in construction has. However, various factors seem to hinder the transformation towards a higher degree of design automation. The first aspect refers to the limited integration and reuse of the product and process knowledge within the CAD system. While in the approaches done by Gross and Sandberg no dynamic integration with the CAD models is proposed, Jensen's study suggests a dynamic integration to only basic parameters of the CAD model, such as the length and width. The suggested consideration of only few main parameters leads to another obvious limitation of the studies. To continue the design process, the obtained product parameters need to be transferred to other CAD systems, where the design detailing of the building components and the corresponding production specifications is performed manually. And finally, even though well-defined product information is seen as a key aspect in increasing the productivity in construction (Lee et al., 2006), none of the studies proposes a suitable technique for making visual the product and process knowledge. Without a clear definition of the product geometry the implementation of variant design automation is done in an unstructured way and thus becomes rather challenging (Hvam and Ladeby, 2007).

### ***Geometric modelling for knowledge-based engineering***

As described previously, in order to achieve significant efficiency improvements, more comprehensive configuration solutions that contain detailed design information and which define the parametric boundaries of the product variants need to be developed. Since a higher level of design detail increases the complexity of the product geometry, suitable techniques have to be used to communicate the spatial structure and the corresponding geometric rules of the elements under study. Such a detailed product documentation is in particular needed, when rules, constraints and dependencies have to be defined to be incorporated in the CS (Hvam and Ladeby, 2007). The literature dealing with capturing, storing and representing geometrical design knowledge suggests different modelling techniques for describing a product model. Research done within the CAD domain typically tries to use models that are close to the environment of a CAD system. The described modelling methods are therefore mainly based on sketches and on 2D drawings which use predefined notation for symbols, lines, arrows and dots. Together with simple if-then-else expressions, the drawings are used to express the geometrical constraints and the object behaviour of the parametric models (Lee et al., 2006). The main purpose of the so called Building Object Behaviour (BOB) description is to provide constructability guidance to architects and to reduce the communication cycles with the structural engineers (Cavieres et al., 2011). Therefore, incorporating knowledge of the geometrical constraints directly in a drawing helps to make visual the spatial design intent to architects and technical drawers in an intuitive way. But at the same time it also hampers describing the parametric relations needed for defining the configuration constraints in a formal mathematical way.

A more accepted method for representing geometry-oriented product models, that are to be incorporated in the knowledge base, is the use of class diagrams and generic product trees or PVM (Haug and Hvam, 2007). Such a formalized description not only better provides an overview of the product variants and the dependencies of the parameters, but also serves as the basis for the subsequent mathematical formulation of geometric constraints within the API. The examples found in the literature are generally based on established modelling standards for products and processes, such as the Unified Modeling Language (UML) and the Integrated Definition (IDEF<sub>x</sub>) methods. Despite the formalized structure, the used product models reveal some restrictions in providing sufficient information on the design intent and the topology of the product that is to be developed in the CAD system. Even if a defined product model captures all geometric dependencies of an object, it still does not provide any information on how to construct it in the CAD system, what the determining parameters are and accordingly how to define parametric constraints in a structured way. In order to achieve a wider acceptance in the construction industry for using KBE and automating the (detailed) design process, a well-defined framework and easy to use tools are needed.

When summarizing the results found in literature dealing with applying KBE and geometric modelling in construction, the following hypotheses on how to achieve higher level of design automation can be proposed:

1. The design knowledge of a product should be dynamically integrated within the CAD system
2. Suitable modelling techniques have to be used for making visual the design intent and the topology of the product
3. The use of KBE should aim to cover a wide range of the design process
4. The design knowledge to be incorporated should obtain a sufficient level of design detail

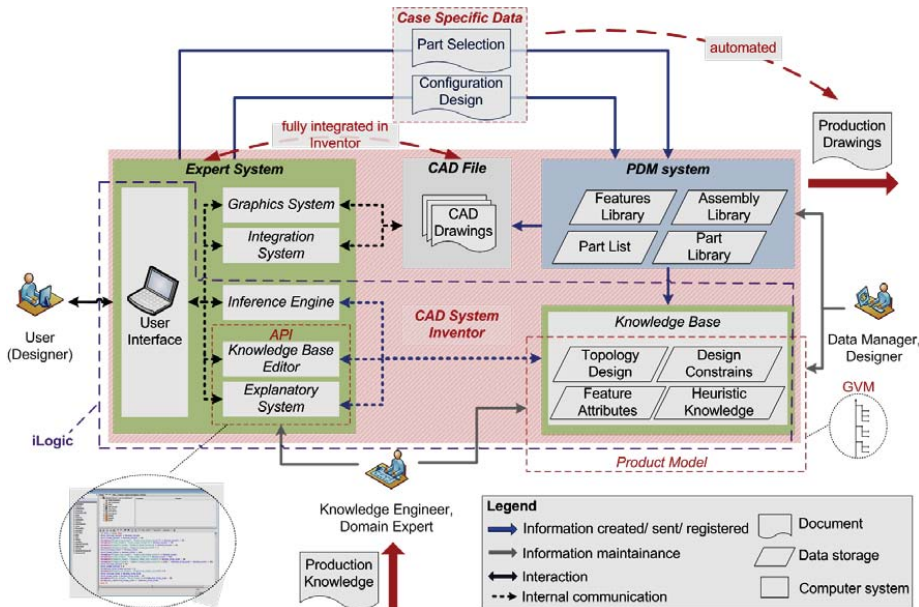
The following sections deal with the question of how redesign the current way of using KBE within the building industry, while keeping the newly developed hypothesis in mind.

### ***The precast industry example***

The use of knowledge-based systems for industrial applications has excessively been discussed in literature (Hopgood, 2011). A growing number of cases, where in particular expert systems have been applied successfully, has helped to implement best practices and common concepts. As described in Section 2.2, Hvam et al. (2008) present a comprehensive procedure for the development, implementation and maintenance of CSs, which are a typical example of expert systems. With this regard, a seven step approach is suggested as a guiding framework for organizations that are dealing with ways on how to implement mass customization, reorganize their way of working and make use of supportive IT tools to streamline their business processes. The industry cases described in this context are typically operating within the electrical, automobile and machine industry, like APC, Dell, Scania, Danfoss and others. As in the mentioned examples product configuration has predominantly been used for making calculations and defining optimal combinations of parts and features, in the building industry, a higher focus has to be set on designing and visualizing the products and its components, i.e. buildings and walls, windows etc., respectively. Therefore, in the following paragraph the well-established framework for using knowledge based systems have been adopted to the context of the precast construction business

The presented industry case produces in average around 7000 precast elements per year, where for each of the elements detailed design drawings for production have to be made. According to the company, it would usually take up to three hours for the drawers to make these drawings, with varying expectation on quality. In case of a partial or full automation of this part of the design process, the manufacturer could increase the quality and free up a high amount of the resources spent on the repetitive design tasks and reallocate them to-

wards the foregoing creative work. Both, the literature and the researchers own investigations therefore show that the highest potential for implementing KBE is for the detailed design, where the design decisions are done on a routine basis and CSs can easier be implemented, as the integration to only one CAD system needs to be realized. The resulting system architecture of the expert system, the CAD and the PDM system, and the knowledge base is displayed in Figure 4-7 below.



**Figure 4-7: Integrated IT system architecture for automated precast design**

Depending on the type of CAD system, different abilities of integrating it to the expert system exist (Hvam and Ladeby, 2007). The displayed system architecture used in this case suggests a CS with a dynamic visual interaction to the CAD system. The graph corresponds to the specific CAD system that is used by the studied precast manufacturer. It outlines how in case the commercial CAD program Inventor 2012 together with the built-in CS iLogic (Autodesk Inc., 2013) is used, the CAD system and the expert system can be realized in a fully integrated way. In case another commercial CAD program and CS are chosen, such as SolidWorks and Tacton Works Engineer, the integration between those two systems would be realized slightly different, while the rest of the IT system architecture would remain the same.

Compared to manually performed design processes, by using the build-in CS the work of the designer, i.e. user of the CAD system, could be changed drastically. The designer would be able to use suitable templates, containing information from the knowledge base of a precast element, directly within the already familiar environment of the CAD system. The built-in CS iLogic would guide the user through the control parameters via a user interface. Based on his input, the design of the element could be done in an automated way, while a production drawing would be produced of the configured element design and selected parts. This information would then be stored in the product data management (PDM) system and could then be sent further to production. A data manager and a knowledge engineer would maintain the system, as they interpret the design information from PDM system and the restrictions and preferences derived from the production. The created parametric constrains would directly be implemented in the system, by using iLogic's API. The used

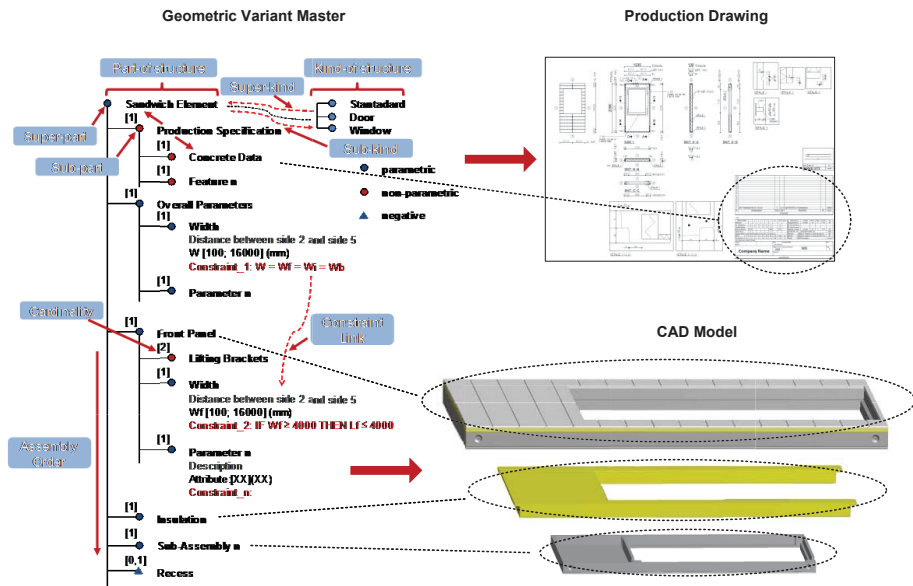


Figure 4-8: Geometric variant master as a template for the knowledge base

In order to record the design information for the knowledge base appropriately, a new way of product documentation is suggested. A so called Geometric variant master (GVM) should be used to capture the relevant geometrical knowledge of the product, as well as to communicate the product architecture and the design intent across the organization. The method is based on the discussed product modelling techniques of the PVM, where additional notations were defined to better obtain the topology of a CAD model, as well as to include specifications for production. As illustrated in Figure 4-8, the first part of the GVM specifies the information, which is needed for producing a concrete element, such as the concrete recipe, the surface quality or the transportation weight. Further down, the assembly order and the topology of the product model is described. The developed notation helps highlighting the occurring parameters that need to be incorporated in the CS, including the design restrictions, the parametric constraints and the “negative” parts that are being used to suppress material

#### 4.3.1.3 Conclusion

Even though the use of KBE to support and automate the design process has widely been discussed in academia, analyses show that the current applications of KBE in construction reveal some major limitations, in terms of degree of design automation and design detailing. To overcome these limitations, a framework for using CSs, as a widespread example for knowledge bases systems, has been introduced and adopted to the construction business. The introduced methods and techniques have exemplary been applied on an industry case, an ETO manufacturer of precast concrete elements. The achieved results demonstrate the promising potential of using KBE for geometry oriented models, as the majority of the routine design tasks could be automated and engineering and design recourses could instead be reallocated to the more creative phase of the design activities. However, in order to cover a wider range of the design process, besides focusing on routine design tasks, design automation could be supported by a higher degree of modularization of the building components and their interfaces and by better working data exchange standards. This would enable to postpone the customer order decoupling point of engineering towards a MTO strategy (Wikner and Rudberg, 2005). Instead, in its current setup the CS support is best fitted for

the detailed design work. The discussed GVM moreover supports the understanding for answering the third research question (RQ3: How should architectures for mass customizing ETO products be designed and managed?).



### 4.3.2 Paper D: Revision and method extension

**Title:** **New complex product introduction by means of configuration**

**Published in:** Proceedings of the 15th International Configuration Workshop, August 29-30, Vienna, 2013

**Case studies:** #7

#### 4.3.2.1 Research objective and research question

In contrast to *Paper C*, this study addresses the second research question *RQ2* from the perspective of the introduction of a new product family within the building sector. The motivation for the study arise when initial literature investigations revealed that little empirical studies have explained the effective introduction of new customized products (Slamanig and Winkler, 2011). Notably the use of CSs has seldom been discussed in the context of radical innovation processes (Hara and Arai, 2012). Thus considering the challenges of dynamically changing markets and increasing product complexity, further guidance based on empirical evidence is needed. Especially for ETO manufacturers which are moving from an individual customization to towards a partly MC approach these challenges are particularly important. The emphasis of this study is therefore to investigate how new products can be launched effectively in situations in which product complexity (internal complexity) is rather high and where only little information about the customer requirements (external complexity) exists. A particular attention is thereby paid on how CSs can support product innovations for significant product renewals.

#### 4.3.2.2 Research contribution

##### ***Recent trends in product innovation***

As elaborated in Section 2.2, integrating the different customization domains into the configuration process helps to provide salesmen with more accurate estimations of time and cost of existing products. However, over time competition forces firms to update their established product portfolio. Smith et al. (2012) discuss two major reasons for companies to regularly work on product innovation:

1. customers change requirements, and
2. product performance needs to be constantly improved

Hence, in the first case new products are only introduced when considerable large discrepancy exists between customer needs and the provided functionality of existing products. In the latter case new ideas and technologies keep customers engaged with the products and thus stimulate sales (Howard et al., 2011).

In majority of the cases, working on product innovation is typically based on existing products, where often more than 70% of the development tasks are related to redesigning, improving, and extending the products offered to the market (Ullman, 2003). To achieve high productivity in the innovation, companies are on the one hand pressured to employ adequate tools and methods that allow an in-depth understanding and managing of knowledge related to products, processes, as well as to their project environment (Vezzetti et al., 2011). On the other hand, to compete on dynamically changing markets, it has become essential to transform the innovation process from a linear to a spiral model with short and direct iterative loops and feedback cycles (Cooper and Edgett, 2008). By doing so, initial ideas and prototypes are immediately tested, where early feed-back is used for further development (Salvador et al., 2009).

As technology is progressing and being used in more and more areas of business, recent studies demonstrate that a high level of technical assessment in innovation significantly improves companies' business performance. With the use of advanced technologies, probable solutions, risks and potentials can initially be evaluated. Moreover, when considering the costs and benefits from suitable technology in early stages of the innovation process, the need for technology alliances can upfront be detected (Cooper and Edgett, 2008).

### ***Product configuration, innovation and vendor collaboration***

Despite CSs are playing an essential part in the customization process of manufacturers, in academia their use has typically been limited to streamline specification processes of matured and well established products, usually offered by one vendor (Blecker and Abdelkafi, 2006; Forza and Salvador, 2008; Hvam et al., 2011). Forza et al. (2002) for example discuss the use of a CS in support of the order acquisition and fulfillment process of products from one vendor with high but relatively simple product variety (Forza and Salvador, 2002a). Hvam et al. (2006) argue for the use of CSs as a way to improve the quotation process of ETO products or even systems. By calculating budget quotations, the CS manages to create sufficiently precise price estimations offered by one company (Hvam et al., 2006). Also Haug et al. (2012) investigate the use of CSs in several manufacturers of rather complex and engineering intensive products. The authors illustrate the employment of different CS development strategies in support of specifying the existing product portfolios (Haug et al., 2012).

Wang et al. (2009) introduce a framework for assessing configuration changes of exiting products. Based on the operational performance of suppliers, a generic algorithm is used to calculate how a changed part affects the preference for individual suppliers. The framework is exemplary tested on a simple electronic device. Even though the authors include the collaboration of several vendors into their framework, stable products with only minor product changes (different product variants) for relatively simple products have been examined (Wang et al., 2009). Ardissono et al. (2003) propose a theoretical framework for the use of a web-based CS which strives to enable the collaboration between different vendors. The authors however omit to explain how the CSs should be used in praxis, especially with regard to complex products and radical innovation (Ardissono et al., 2003).

### ***A Procedure for implementing complex product configuration in NPD***

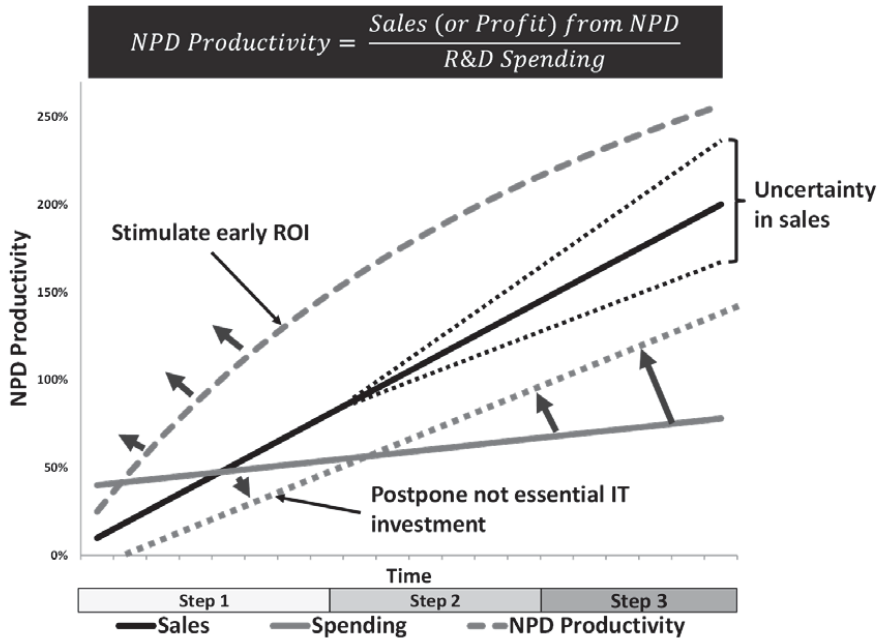
By implementing CS several benefits can clearly be gained. Yet, when planning and performing configuration projects with complex products and multiple users, the desired results are often not being achieved. According to Haug et al. (2012) a major challenge for the success of a configuration project is that for complex products, the configuration task is difficult to be estimated. In result projects often become significantly more costly than anticipated or companies fail to create prototypes that indicate the potential benefits. Another reason for abandoning initiated configuration projects is that by implementing a CS a substantial part of the business processes have to be redesigned. In case the required organizational changes are not widely accepted by the employees, the system will most likely not be used (Haug et al., 2012). To overcome these challenges it is important to establish a clear innovation strategy that promotes configuration projects which are likely to succeed and where the risk for failure is kept to a minimum. Thus, to be able to make reasonable decisions about the right innovation strategy it is inevitable to make use of relevant performance metrics. A way of assessing the performance of NPD is through monitoring the NPD productivity measured as the output from the NPD process divided by the input (Cooper and Edgett, 2009):

#### **Equation 4-1: New product development (NPD) productivity**

$$NPD \text{ Productivity} = \frac{\text{Sales (or Profit) from NPD}}{R\&D \text{ Spending}}$$



As indicated in Figure 4-9 below, in today's quick changing business environment the outcome of the NPD can be rather uncertain. Estimations about long term sales development of new products remain vague and can cause high risks with regard to their success on the market (Oriani and Sobrero, 2008).



**Figure 4-9: The effect of sales and spending on NPD productivity**

In order to increase the NPD productivity and reduce risk of failure in the more reliable planning horizon, i.e. at an early stage of the innovation process, early research and development (R&D) spending should be kept low. For ETO firms moving towards MC this can be achieved in two major ways. First, it is beneficial to establish strategic alliances with reliable suppliers. By sharing and coordinating innovation activities for complex products and knowledge about customer preferences and trends, individual investments and risks concerning the success on the market can be reduced (Pullen et al., 2012).

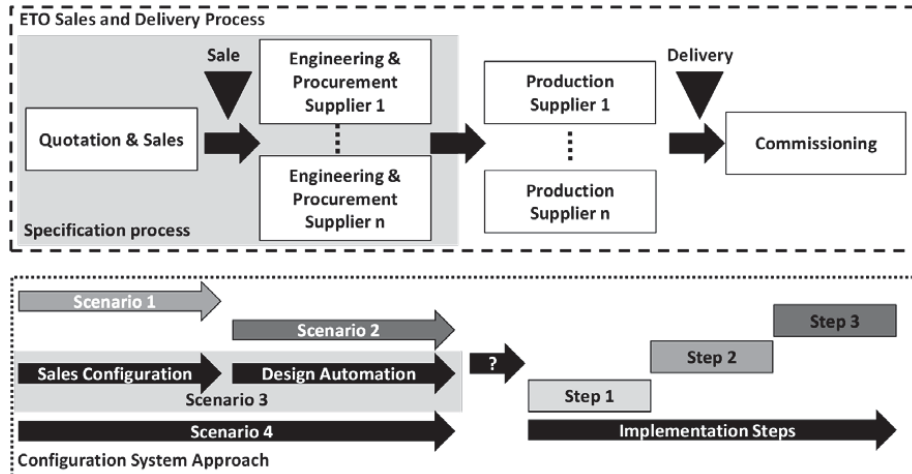
Secondly, for configuration projects the R&D spending is mainly driven by the development of the configuration model and by the related IT investment. At an early stage of the configuration project it is therefore important to be clear about what are the essential "need-to-have" functionalities the CS needs to have and which of the possible functionalities can be categorized as "nice-to-have". As the product is maturing over time and turnover from sales is increasing, further investment towards the less prioritized functionalities can be taken and the use of the CS can gradually be extended. From a financial perspective a strategic alliance and a stepwise configuration development stimulates an early return on investment (ROI) and increases the probability for more successful new product launches. Furthermore, a stepwise implementation encourages employees to embrace the organizational changes caused by the system, while its functionalities are being extended over time.

In sum, by involving the strategic partners in the configuration project, investment and risks can be shared and a wider range of the specification activities can be considered. Having set the requirements for the innovation strategy, in the following steps the some essential characteristics of the project life cycle will be discussed.

### ***Designing the implementation approach***

For companies delivering ETO products a common purpose of having a CS is to automate the sales and ordering process (Haug et al., 2009). In result, this initial analysis of the involved specification activities helps to assess the requirements for the subsequent automation.

Depending on the scope of the project, CSs can potentially be implemented to support wholly or only partly the specification process (Hvam et al., 2008).



**Figure 4-10: ETO specification and delivery process with a stepwise scenario implementation**

Next, a TO-BE specification process supported by the system can be defined. Scenario 2 in Figure 4-10 illustrates the most widespread approach for CSs (Salvador et al., 2009), namely a sales configurator. In other less common situations, ETO companies might have more benefits from the implementation of a solely technical support (Scenario 2). In such a case the system would function as a design automation system for generating technical specifications for production. Due to the involvement of complex calculations, a major challenge is thereby to cover the entire technical specification (Elgh, 2008). Next, the simultaneous implementation of both, a sales and a technical configurator is repressed by the remaining two scenarios. While in Scenario 3 two separate systems would cover the two aspects, Scenario 4 represents an integrated solution for the configuration. However, as the integration to other IT systems and to advanced calculation and CAD applications, such as to Mathcad and Inventor, is a major cost driver, in the first step this investment it is often unfeasible.

More recently, researches have investigated the use of configuration systems not only as sales tools, but also in support of the entire specification process, i.e. the order acquisition and order fulfilment process (Forza and Salvador, 2002a). Helo *et al.* (2010) for instance propose a business model for the use of CSs throughout the entire specification process of a product (Helo et al., 2010). The authors discuss how sales configuration can first be used to translate customer needs into functional requirements of a product. In the physical domain, product configuration then matches the chosen set of functionalities into design parameters. Even though not implemented in the study, process configuration can eventually be used to select on a high level suitable production and logistic steps for the subsequent processes.

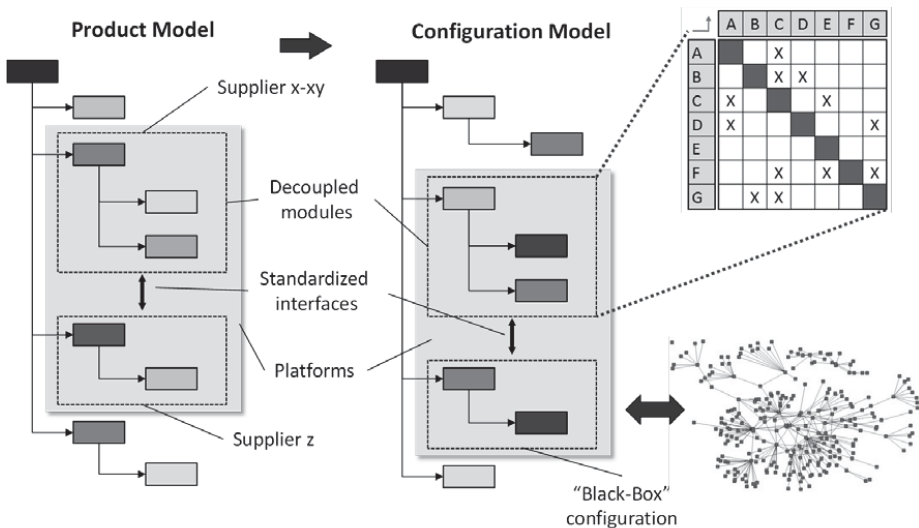
Consequently, though the use of advanced CS can potentially sustain the entire specification process (Scenario 4), to keep the investment costs and the organizational changes at a low level, in the first step (Step 1) of implementation, only the needed process steps are to be assisted by the system. In the subsequent steps (Step 2 etc.), more and more activities

related to the specification of a product can be automated. In the majority of the cases it is feasible to start with the development of a sales CSs, as for example investigated by Salvador et al. (2009). Such a system could then be used as a marketing tool, where in the introduction and growth phase of the product life cycle the focus is on creating customer awareness of the product and on trial of different product variants (Kotler et al., 2012). With the right analytical capabilities (Frederiksen, 2009), companies could quickly uncover customer preferences and thus further extend their product portfolio towards the required product features.

The described framework for using CSs in the process of NPD of complex ETO products was tested for validation on an industrial case study. The thereby gained results will in the following be briefly discussed.

### ***Aligning product analysis and development with configuration development***

Since in most cases product innovation builds upon existing products [Smith *et al.*, 2012], after clarifying the implementation steps, an analysis of the most similar product architecture needs to be taken. For the analysis of the architecture, often the Quality Function Deployment (QFD) and the Design Structure Matrix (DSM) have widely been utilized. With their help customers' needs are identified and linked into the created product structure (Vezzetti et al., 2011). The employment of the Modular Function Deployment (MFD) then enables the creation on decoupled functional units, i.e. modules (Ericsson and Erixon, 1999).



**Figure 4-11: Aligning analysis model with computer model**

Another way of representing the product architecture is through the hierarchy structure of the PVM technique. Though, regardless the chosen modelling technique, with product platforms in the development process are more stable product architecture can be achieved (Meyer and Lehnerd, 1997). To ensure the collaboration between suppliers of a complex product, the individual components should be integrated as separate modules with decoupled functionalities and with clear interfaces to the related product components. Figure 4-11 illustrates the integration of components coming from different vendors into the entire product model. While some of the modules may be delivered from different suppliers (indicated by "x-xy" in the figure), for other modules only one supplier ("Supplier z") may exist.

An analysis model generally aims at representing the physical components and their functionalities. From an object oriented perspective, the development of a computer model however characterizes the logical combination of classes and their attributes. Each class may represent physical components or other important product characteristics. Such characteristics could e.g. describe geographical, geometrical and functional product aspects, such as the targeted market or the shape and style of a product. Depending on the modelling environment of the CS, as indicated in Figure 4-11 the computer model can then be illustrated as a PVM.

Even though the composition of the configuration model might be slightly different from the one of the product model, the same structural concerns are relevant for its knowledge base. Thus, since a growing product complexity typically leads to an increasing configuration complexity, wherever possible the configuration structure should consist of separate configuration modules (classes) with encapsulated constraints (Tiihonen et al., 1996). To simplify the model, also here standard interfaces among modules with a minimum number of cross related constraints are beneficial. Classes which can be carried over across product families are then to be grouped to platforms.

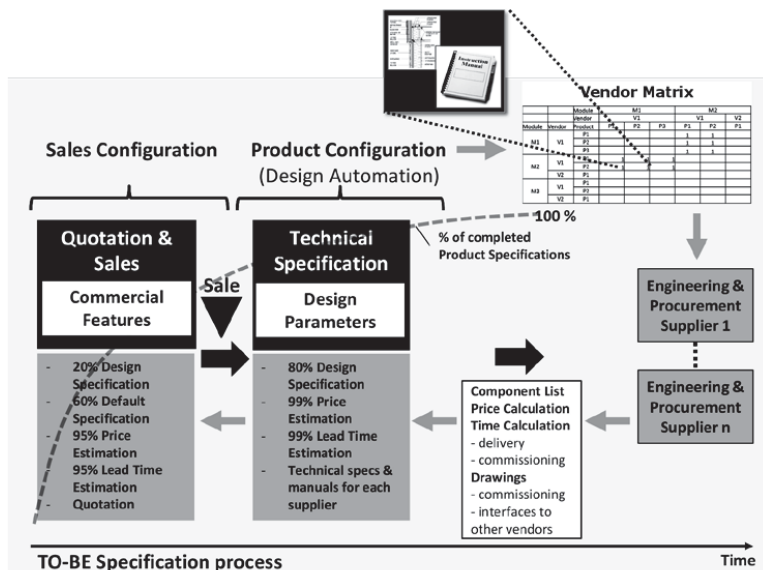
Furthermore, in cases where the final product components are unclear yet, a Concurrent Engineering like approach can be achieved by the use of a "black-box" configuration (Whitney, 1988). In this case configuration classes which contain dummy attributes and constrains for the presumed product functionalities (attributes) can be established in parallel to the development of the physical product components. Once the final components and the corresponding supplier specifications are available, the placeholders created in the CSs can be fed with the actual information. Finally, by using the spiral model (Cooper and Edgett, 2008), a quick trial and error testing of the CS helps to detect critical configuration aspects and product components for which the product information is yet fragmented or not available.

### ***Developing the TO-BE specification process at the case company***

Having established an overview of the AS-IS specification process, a TO-BE specification process for a stepwise CS implementation was created. The main requirements for Step 1 were:

1. The specification errors, long lead times and limited product representation should be improved by the use of a sales configurator.
2. The sales configurator should:
  - a. Contain only product features which are essential for the customer.
  - b. Store not essential product features as predefined default values and represent for the majority of the cases a well-designed product (Mandl et al., 2011).
  - c. Be available locally on salesmen's computers.
  - d. Provide a sufficiently accurate (95%) price and lead (delivery) time estimation.
  - e. Provide a 3D graphical user interface (GUI) of the product, where a direct impact of the configured commercial features on time and cost is to be seen.
  - f. Generate a quotation for the customer including a description of the configured product.
  - g. Save the customer's information and the configuration status for a later reconfiguration.
  - h. Enable the selection of non-standard choices for better adaptation of the offered solution space.
3. The remaining specification process should be divided into a configurable technical specification process and into a non-configurable engineering and procurement process.

4. The configurable technical specification process should be supported by a technical product configurator, the remaining specifications should be created in a traditional manner (through CAD and advanced calculation systems).
5. Both, the sales and the technical CS should be based on the same configuration model.
6. The output of each of the SCs should work as input for the other SC.
7. The (technical) product configurator should:
  - a. Contain all design specifications of the product which can be configured within the CS.
  - b. Be available on the intranet.
  - c. Estimate price and lead times (production, delivery, commissioning) as accurate as possible (ca. 99%).
  - d. Contain only basic descriptions and static pictures of the product.
  - e. Generate technical specifications and manuals for the involved suppliers.
  - f. Save the configuration status for a later reconfiguration.



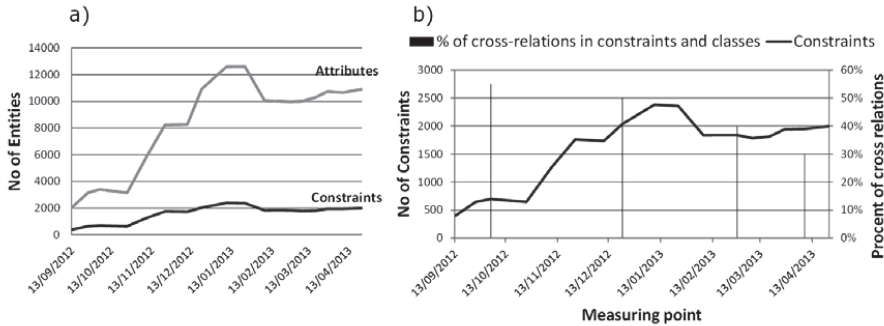
**Figure 4-12: T0-BE specification process of the case study**

Figure 4-12 shows a high level representation for the chosen initial CS implementation (Step 1). To meet the requirements, a variation of Scenario 3 was selected. For the later steps of implementation (Step 2 etc.), the sales configurator should be available on the internet, where a wider range of customer awareness can be achieved. Another aspect e.g. concerns the functionalities of the technical CS. In later stages the system could have a direct integration to various CAD and calculation software, so that a higher percentage of the whole product specification can be created. However, since the product consists of components from a number of different suppliers, currently a complete definition of these 3rd party components appears to be unrealistic.

### *Developing a configuration model at the case company*

A generic product model for yet to be developed product family was created by means of the above described modelling techniques. The corresponding configuration model was done directly in the chosen configuration software. Since both, the product and the config-

uration model were extended over time, the solution space of the models increased dramatically. Figure 4-13 displays how the number of attributes and constraints of the configuration model grew as it was further completed. The growing complexity of the configuration model led to a higher computation time and to less control over the behaviour and the cause-effect relationships of the system. Hence, several initiatives were taken to reduce the structural complexity of the model. Two of them will in the following be discussed.



**Figure 4-13: Progress of the configuration model**

To simplify the product structure, first the yet rather integrated construction of the model was redesigned to a more modular form. As described in the framework, wherever possible, it was tried utilize modularization, i.e. to make use of encapsulated classes and thus to reduce the number of cross relations. Figure 4-13 shows how despite a further extension of the model, a decrease from 55% to 30% cross-relations in the model considerably reduced the number of needed constraints. Moreover, having encapsulated classes with little cross-relations provided a better overview over the entire configuration model and facilitated the inevitable debugging. In cases of unexpected behaviour, computation or even system errors, the responsible classes could easier be detected.

Another way to reduce the complexity of the configuration structure was to minimize ranges of attributes. Since not every technically possible attribute value is required by the customer, the characteristics of each attribute could be reduced to the tolerance limit. Table 4-4 exemplary depicts how a simplification of 4 attributes exponentially reduces the solution space and hence the structural complexity of the knowledge base. Instead of using the technical possible solution, by limiting the ranges with factor 100 the solution space could be reduced by factor  $10^8$ .

**Table 4-4: Reduction of unnecessary attribute values towards tolerance limit**

Solution Space of 4 related attributes for Component A and B		
Category	Solution Space (No. of Combinations)	Structural Complexity
Technically possible	19,360,000,000,000	100%
Simplified each attribute by factor 10	1,936,000,000	0.01%
Simplified each attribute by factor 100 (tolerance limit)	193,600	0.000001%

#### 4.3.2.3 Conclusion

When following MC, manufacturing companies have to consider a number of characteristics. The internal and external complexity is thereby seen as a major challenge to be handled. Especially for ETO companies the movement towards MC seems to be much more complex compared to mass producers. Their products typically comprise a low degree of standardization with no or little commonality, their processes are seldom automated and they have

little control over their customer portfolio. This study shows that in order to better cope with arising challenges, ETO firms need to pay a particular attention on the planning phase of a new product introduction and the related product configuration development. Besides the foregoing product and process analysis, several additional aspects need to be considered:

1. ETO companies using product configuration should collaborate on innovation to reduce risk and investment and to become more efficient with the new product launches.
2. CSs should be planned and implemented in steps by using the spiral model, starting only from the most important “need-to-have” functionalities first.
3. CSs should consider the product lifecycle objectives of products, focussing first on the creation of awareness and trial of product variants.
4. Efficiency can be gained in later steps of implementation, as functionalities are being extended, and automation and further integration to other IT systems is realized.
5. The product structure of new products needs to be redesigned in order to be configurable, while 3rd party components should preferably appear as separate modules with standardized interfaces.
6. Analysis model and computer model can be created simultaneously, with a focus on stable and well known components. For yet not finally designed components dummy classes with estimated functionalities can be created.
7. In order to handle the complexity of the knowledge base, the computer model needs to follow the same objectives as the analysis model, namely; (a) the use of generic and modular yet encapsulated configuration classes with little cross related constraints (standardized interfaces), (b) the implementation of standardized and decreased attribute ranges.

Apart from providing additional insight for answering *RQ2*, the conducted research confirmed some of the theoretically elaborated aspects with respect to *RQ3*. In particular, the case study clarified the importance of an aligned architecture design process, which considers both, the in Section 3.1.2 described analysis model and computer model. Moreover, several structural complexity measures were implemented to reduce the present system complexity.



### 4.3.3 Paper E: Method detailing and refinement

**Title:**                **How to Scope a Product Configuration Project in an Engineering Company**

**Published in:**    International Journal of Industrial Engineering and Management (IJIEEM), pp. 207-220, earlier version originally published in: Proceedings of 6th International Conference on mass Customization and Personalization in Central Europe (MCP-CE 2014). University of Novi Sad, 2014.

**Case studies:**    #11

#### 4.3.3.1 Research objective and research question

*Paper C and D* provided a deeper understanding of how the support of specification processes can be organized within the construction industry. This paper reflects upon the described approach and refines it within the context of process plants and machinery applications. Experiences within the research group of the author from projects in this kind of companies reveal that often confusion and lack of focus occur already from the first steps of the project to its final release. This lack of focus often results in both, limited the performance of the CS and increased time and resource consumption for developing and implementing the CS. Acting upon this challenge, this paper suggests a framework for scoping the product configuration projects for companies with complex and highly engineered products. This framework is based on a general and well-established framework for scoping IT-systems and on specific methods for modelling a product CS. The main results will be discussed in the following sub sections. Further details on the paper content are to be found in Appendix E.

#### 4.3.3.2 Research contribution

Based on a thorough evaluation from theory and the gather experience in praxis, the following list for creating systematic CS implementation is suggested:

1. Aims and purpose for the CS and overall process flow
2. The identification of stakeholders and their requirements
3. IT-architecture incl. flow in the CS, UI, input, output, integrations, and the main functionality of the CS
4. Products and product features to include in the CS, incl. level of detail
5. A project plan incl. resources, time table, modelling approach, test and development, system maintenance, etc.

#### **Case study**

The proposed framework has been applied in a real context to assess its functionality. The case company is an international company specialised in the production of heterogeneous catalysts and in the design of process plants based on catalytic pro-cesses. The Wet Sulphuric Acid (WSA) process is used in industries like oil refining, coking, coal gasification and viscose fibre use.

#### **Aims and purpose for the configuration system**

A main challenge for the WSA process plant in the case study is within sales and pre-engineering, because a long time (more than one week) was needed to make a quotation. The regional offices all over the world are not capable of making the quotations themselves because of the complexity of the WSA.



The purpose is to introduce a CS, which can act as a knowledge management system, to provide easy access to product information and offer a simple way of making quotations. The system will reduce the lead time for generating quotations for sales people and act as a presale technical CS. Therefore, a major objective of implementing a CS is to make the sales process more effective. The system empowers salesmen to act more independently from the technical experts. Hence, in this project, the use of a product configurator will lead to:

- Reduced lead time in sales and engineering processes
- Improved quality of machines and plants
- Increased sales – as it becomes easier to generate quotations
- Reduced complexity of machines and factories
- Cost savings in sales, engineering, production and installation due to the use of product configuration and more well defined and standardised modules in the projects
- Improved accuracy in cost calculations and a decrease in projects that go over budget

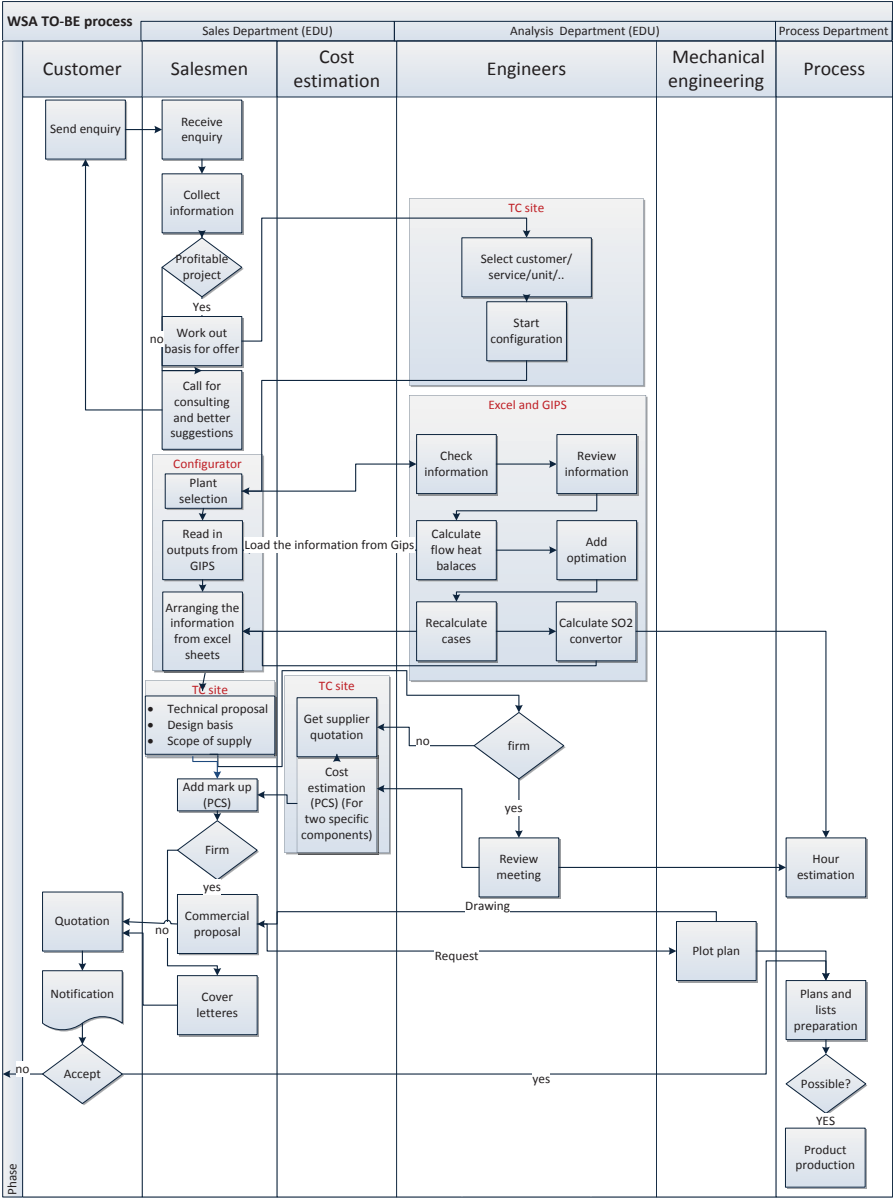
In order to describe future scenarios, it is necessary to have a comprehensive overview of the current situation. Sales people are currently using excel sheets and a complex home-made calculation systems as the main foundation for the creation of technical proposals. The calculation system is a way of calculating a complex chemical process. Another problem is that the time spent on generating a quotation is not competitive in comparison to other companies around the world. The purpose of the project is primarily to create a stable tool aimed at generating proposals with as few errors as possible. The accepted scenario is shown in the flowchart in Table 4-5 below.

### ***Stakeholders' identification and requirements***

In this case, the stakeholders are sales staff, cost estimators, product developers, marketing staff and regional offices with different requirements to the CS. The aim is to find a way to integrate the complicated calculation software into the CS and make it easier for sales people to get involved in the calculating process. The overall requirements for the CS are:

- Configure a process plant based on feed stream properties and requirements in terms of the emissions of a specific plant type (all stakeholders)
- Combining document snippets into full technical or commercial proposals (sales people and cost estimators)
- Loading technical and commercial data from the configurator into tables (sales, cost estimators and marketing group)
- Price calculation, bills of material and scope of supply (all stakeholders)
- Integration with high performance calculation systems and other systems for receiving the calculated outputs and flow diagrams (all stakeholders)
- A user friendly and independent solution (all stakeholders)
- Currency and language versions (regional offices)
- Online based and saving functionality (sales)
- Easy access to maintenance and updating the system (sales people and product developers).

Table 4-5: TO-BE process example



Summary of the case study

In the case company the framework was used in the initial phase of the configuration project in form of a checklist of issues to clarify in the initial phase of the project. By following this “checklist” the configuration team and the stakeholders had a better basis for defining the project and establish a common understanding of the CS to be developed from an early point of in the project. During the project execution the scope developed served as a project definition for the configuration team and as a contract between the configuration team and the stakeholders. During the later phases of the project the initial scope was used and adjusted

whenever new requirements arouse from the stakeholders or other changes in the configuration project had to be made.

#### 4.3.3.3 Conclusion

The suggested framework (plan) for well scoped specification system support of projects is developed based on literature and based experiences from implementing product configuration projects in other ETO companies such as: GEA , MAN Diesel and Turbo , APC , FLS-midth , CIMBRIA , NOVENCO , ALTAN , and EMERSON. All these companies are producing complex and highly engineered products like the presented case. These companies are similar from different perspectives. Firstly, they are all producing highly engineered and complex products and they all want to use the product CS as a solution for de-creasing complexity; and make the sales and engineering processes more efficient (Von Hippel, 2001). Without a clear scoping from the first stages the CS tends to get complicated and with lack of focus. Secondly, similarity is that they are all using the CSs for the sales and pre-engineering processes. Thirdly, they work on a high level of abstraction for the configuration projects. The stakeholders for all these companies are highly experienced engineers and sales employees. The CS is new to these people, so the configuration team need to discuss the scope with sales people and engineers with no particular knowledge or experience on product CSs.

This paper clarifies that having a standard framework for implementing configuration projects has a remarkable effect on decision making in the early phases of a project. The suggested framework for scoping a CS has been tested in a case company. In the case company the framework proved to be useful for the project team in supporting an early clarification of the configuration project, and the scope developed formed a solid basis for the subsequent configuration project in that the scope developed helped to focus and give priority only to needed parts of the CS. However additional research is required regarding the maintenance and testing stages.

The case study moreover revealed some challenges in identifying and prioritizing the stakeholders and their requirements, which is a field that needs more researches in the future. Finding a solution for the documentation and maintenance part of the configuration project also need further research. Furthermore, the suggested framework needs to be tested in a number of companies to further validate it, and to test if the frame-work could be used also in other kind of companies than only ETO companies with complex and highly engineered products. Customizing the rational unified process (RUP) methods (Hirsch, 2002), and combining different modelling tools introduce a scoping framework for the configuration project. This scoping is able to clarify a project plan and the time estimation for the project managers and configuration team even before project commencement. The case study indicates that having a framework for scoping including e.g. determining stakeholders' requirements, modelling tools, management of input and output, levels of controlled details, maintenance and documentation is a valuable means for defining and controlling configuration projects.

### 4.3.4 Section summary

In this section, the literature review relevant to answer the second research question (RQ2: How should the specification process of ETO companies moving towards MC be developed?) was extended and supplemented the gained insight with three case studies. *Paper C* introduced in Section 4.3.1 discussed an initial investigation of a specification process support through the use of CS in the detailed design phase of a precast manufacturer. The study reflected upon a situation where limited adjustments on the actual architecture were taken, thereby limiting the scope of the support to a small part of the specification process. Despite the reduced effort, the potential operational improvements on both, the mean and the variability were severe. At the same time, it was recognized that the development of other basic MC capabilities, through e.g. postponement and architecture development, additional gains could be achieved. To overcome this limitation, *Paper D* introduced in Section 4.3.2 emphasized use of specification process support for the introduction of a new product family. The study introduced a framework for a stepwise implementation of CSs in parallel to the development of the architectures. Moreover, a concept for how to coordinate the sales process with the design automation part was introduced for a situation where several vendors collaboratively contribute to the design of the product. Also, the importance of a formal architecture design approach and the challenge of rising architecture complexity was investigated. Next, *Paper E* presented in Section 4.3.3 benefited from experiences gained from the discussed studies and from other related work within the researchers network, to create a detailed plan for defining an adequate scope of specification process support. The results suggested the use of a systematic method. The method adapts established frameworks related business process re-engineering and combines them with relevant modelling techniques to address the particular needs of ETO firms providing complex plants and machineries.

Thereby, this section has answered *RQ2.2* and *RQ2.3*. The interrelation between the architecture design and the specification process require *RQ2.1* to be answered in the next section, were a concept for an enhanced understanding of postponement will be developed.

**RQ2.2:** What are expected benefits, risks and limitations when implementing CSs for ETO products?



**RQ2.3:** How should CSs be used to assist the specification process in ETO companies?



## 4.4 Development of robust system design

This section addresses the third research question (RQ3: How should architectures for mass customizing ETO products be designed and managed?) by first complementing the current understanding of the subject through an initial survey (S1) with employees from manufacturing companies relevant for the research topic. Next, four additional case studies across two different industries were conducted, to test and refine the obtained insights.

### 4.4.1 Paper F: Investigation of architecture development strategies

<b>Title:</b>	<b>The Use of Modelling Methods for Product Configuration in Industrial Applications</b>
<b>Published in:</b>	Proceedings of the 7th World Conference on Mass Customization, Personalization, and Co-Creation (MCPC 2014). In Brunoe, T.D., Lecture Notes in Production Engineering, p. 529-539, Springer, 2014
<b>Survey:</b>	S1

#### 4.4.1.1 Research objective and research question

This study addresses the first two sub questions *RQ3.1* and *RQ3.2*, and empirically validates the use of CSs relevant for validating the understanding of *RQ2.2*. As Section 3.1 discussed, developing product CS requires extracting and representing domain expert knowledge in appropriate product models. As acknowledged by researchers, this is often one of the most challenging activities in configuration projects, where only little empirical insights have yet been reported. This article investigates the challenge on how industrial companies model their product CSs. The study is based on interviews of 18 industrial companies using CSs for configuring customer-tailored products. It investigates the relationship between using a structured modelling technique for modelling product families relative to less or no formal approaches. Furthermore, the study explores the specific characteristics of configuration set-ups with respect to size and complexity and their effect on product variant management and availability of product knowledge in organizations. The results empirically validate the need for a suggested systematic modelling approach for large and complex configuration projects and its positive effect on the overall performance of companies.

#### 4.4.1.2 Research contribution

##### ***Research background***

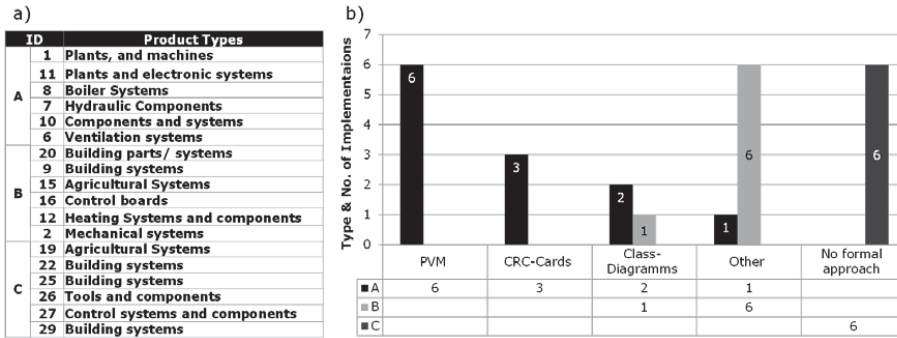
In many cases product CSs have been used to create quote prices, sales prices, bill of materials, and other product specifications. They incorporate knowledge-integrated or intelligent models of the product portfolio. Based on these models, new specifications for product instances and their life cycle properties can be derived. The development of CSs requires that domain expert knowledge is extracted and represented in corresponding product models to be incorporated in a CS. As acknowledged by researchers, this is often one of the most challenging activities in configuration projects (Sabin and Weigel, 1998). However, only little empirical studies investigate the character of the modelling methods applied in industry and their usefulness with regard to nature of the configuration project. Instead, academia typically focusses on proposing various modelling methods based on conceptual examples or single case studies, e.g. (Aldanondo et al., 2000; Chao and Chen, 2001; Tseng et al., 2005; Yang et al., 2009). To better understand this relation, this article evaluates the experiences from applying a structured approach for modelling product variants for product CS in relation to less formal methods. The implementation of a comparison framework for such a systematic approach is examined relative to less formal modelling techniques, e.g. structured

bills of materials, or to no specific methods at all. The qualities of the suggested modelling procedure are yet not compared to other related modelling techniques.

### **Modelling methods used in the case companies**

To investigate the actual use of modelling techniques in product configuration projects, an investigation on the use of product CSs in industry companies was carried out.

**Table 4-6: Applied modelling techniques per category**



A total of 29 companies were interviewed for the study, where a sample of eighteen companies was selected based on: 1) the interviewed being able to explain the modelling techniques used, and 2) the interviewed being able to state the effects from using product configuration. All eighteen case companies offer business-to-business products, where in ten of them, several CSs are in operation. The evaluation of the interviews enabled a general classification of the 18 companies with regards the modelling approach in 3 different categories, with 6 in each category (Table 4-6 a). Table 4-6 b) illustrates the modelling distribution for each of the categories. All companies belonging to category A were using the suggested PVM technique, 3 were using CRC-cards and 2 companies also used class diagrams. Companies belonging to category B reported using structured bills of materials as their dominant way for defining the variants in the product families. Besides, they apply Excel spread sheets, Word documents and the modelling environment provided in the product configuration software. The remaining C companies claimed not to use any specific modelling techniques outside the configuration tool, except of product tables in Excel spread sheets and specification reports in Word documents. The results of the configuration set-up in relation to the used modelling approach are discussed in the following section.

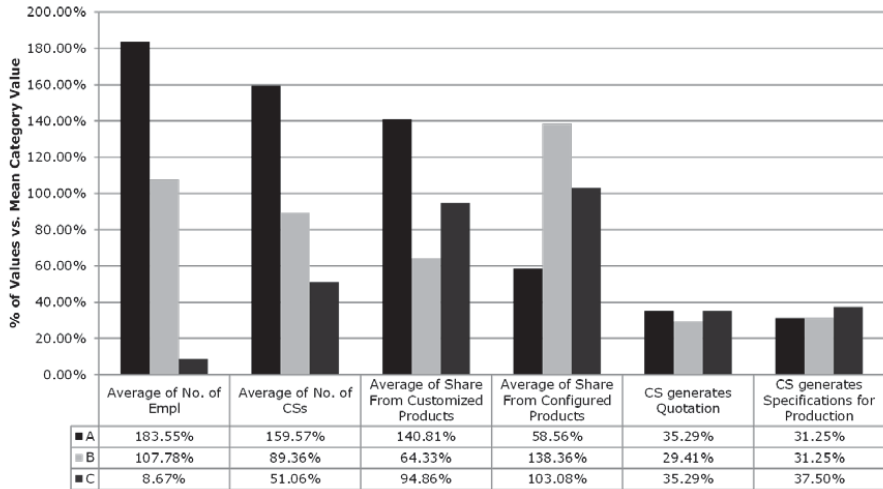
### **Effects of the configuration set-up on company size and market**

Table 4-7 provides background information on the investigated companies and the size and purpose of their CSs. As indicated in the table, CSs are used across all three categories in support of the quotation and production process. More precisely, 17 out of 18 of the companies apply product CSs for quotations. Sixteen of these use the product CSs both for creating quotations and for the manufacturing specifications, while only one company uses product CSs solely for creating manufacturing specifications. In most cases such product CSs were created by using the same standard configuration software shells. In the context of counting the number of product CSs, a single product CS is defined as being each running software application, which has an individual knowledge base.

Companies belonging to category A are typically globally operating firms, which are larger in average (84% bigger than the mean value) and have a high share of customized products compared to configured ones. They are mainly offering industrial systems, plants and machineries, which require a strong engineering effort. To support the customization of their complex products, they have implemented several CSs (60% more than the mean

value). This helps them to configure ca. 30% of their product range, while remaining part of their portfolio today involves additional engineering workload.

**Table 4-7: Background information and configuration support**



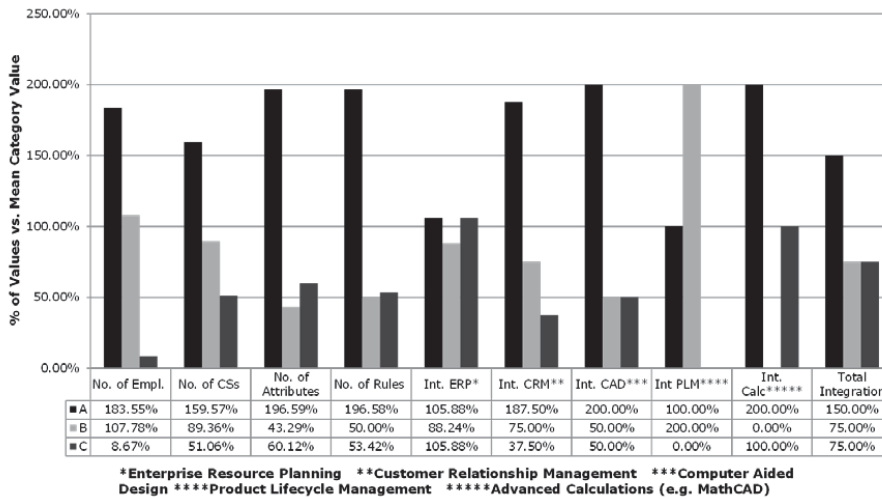
Compared to A firms, companies belonging to category B are in average smaller in size, yet globally operating. They are producing building, agricultural and mechanical systems and use a limited number of CSs for a large part of their product range. Next, C companies are considerably smaller in size. They are typically locally operating firms working within building and tooling sector, where ca. half of their products are supported by generally one CS.

#### ***Effects of the configuration set-up and complexity on the modelling approach***

When investigating the detailed set-up of the individual CSs in the case companies, a major difference can be revealed. Companies in category A use several CSs for relatively complex products and with a strong integration to other IT systems (50% more than the mean value), such as CAD or ERP. In order to handle the configuration tasks, each of their CSs comprise a large number of attributes and rules. Due to the increase challenges in modelling their product portfolio for configuration, all of the A companies were using the suggested CPM modelling techniques. But as the CSs grew bigger and the number of people involved in the configuration projects increased, they realized a need for being able to work in a more structured way and for being in more control of the models implemented in the product CSs. Here, three of the 6 companies using the a systematic procedure have reported that they started to model their product CSs without any specific modelling technique.

As Table 4-8 reveals, companies of category B and C have implemented significantly smaller CSs. Their systems are usually integrated to Enterprise Resource Planning (ERP) or Product Lifecycle Management (PLM) systems, with little emphasis on external integrations to Computer Aided Design (CAD) or to advanced calculation systems. This indicates that with a minor configuration project for relatively simple products and not involving too many employees, the modelling can be managed by using less formal modelling tools. As the configuration task increase in both, size and complexity, the more important becomes a systematic modelling approach.

**Table 4-8: Effects of product configuration complexity on system integrations**



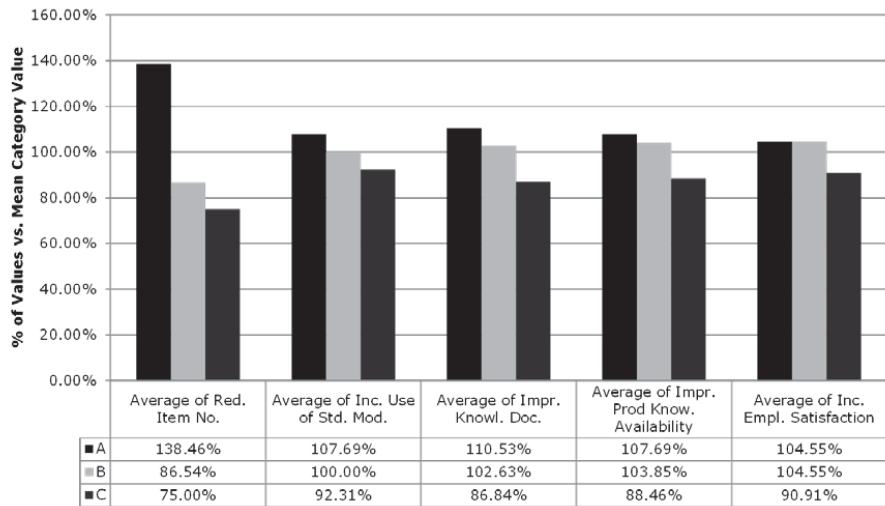
### Effects of the configuration set-up on companies' performance

Finally the impact on the companies' ability to document and share their product knowledge, their ability to reduce the number of product variants in the company, and the degree of employee satisfaction among the employees involved in the product configuration projects was investigated. The respondents have rated the impact on a five-point scale from 1 (strongly disagree) to 5 (strongly agree) and "empty space" for no answer to the question. Here, reducing product variants means the ability to eliminate unnecessary product variants from the product assortment in the company. The ability to keep down the number of product variants (item numbers) in the product assortment is claimed to be an important enabler for reducing complexity and thus keeping down costs in the company (Lindemann et al., 2009). As listed in Table 4-9, A category companies claim to have a better ability to reduce the number of product variants than the others. This may be related to an increased ability to document and get access to product knowledge with the systematic procedure. Companies not using a systematic procedure report to have less documentation of, and access to, their product knowledge. However, the differences between the three groups on documentation and accessibility of product knowledge are not very significant. This could be related to the fact that the companies using less formal modelling techniques are having relatively minor CSs, which handle simpler configuration tasks and where the related complexity can still be managed.

Furthermore, employees working on product configuration projects with the described systematic modelling procedure report to be slightly more satisfied with their working situation than those working with no formal modelling techniques. This may be related to the increased ability to document and get access to product knowledge, which makes it easier for the employees to control the product knowledge implemented in the CSs, and to communicate the product knowledge with colleagues from other departments, such as product development, sales and production.

**Table 4-9: Effects on work environment, knowledge management, product design and quality**





#### 4.4.1.3 Conclusion

The conducted study on the use of product CSs in industrial companies provided new insight into how CSs are modelled and documented in relation to the nature of the configuration set-up. The results reveal that out of 18, 6 companies used the suggested systematic modelling approach, for relatively complex products and sophisticated CSs. The remaining 12 companies used less formal or no formal modelling techniques for less challenging and less advanced configuration projects. Furthermore 3 of the 6 respondents using the systematic modelling techniques have claimed that they started to use the more formal modelling techniques as the number of CSs and thus the configuration projects grew bigger and involved more and more people. They then claim to be more in control of their product knowledge and their product variants than the companies using less formal modelling techniques. This may be partly due to an increased ability to involve domain experts in the modelling process, which secures that the right decisions are being made as to which product variants to include in the CSs. This indicates that in order for major companies to be successful in the use of product CSs in a setup with several CSs with a high complexity and numerous employees (often geographically diversified) involved, a formal modelling technique like the systematic approach is needed. Furthermore, a more formal modelling technique makes it possible to keep track of the product variants, features and rules implemented in the CS. A better communication with the domain experts reflected in the report an increased ability to control the product knowledge as well as an increased level of satisfaction from the employees working in the configuration projects. The study revealed an important correlation between the use of a formal modelling technique (with the systematic approach), the size and complexity of the CSs as well as the ability to control the product knowledge and products variants.

## 4.4.2 Paper G: Revision and initial investigation of robust design methods

**Title:** Utilizing Platforms in Industrialized Construction: A Case Study of a Precast Manufacturer

Published in: Construction Innovation, Vol. 15, no. 1, pp. 84-106, 2015

Case study: #8

### 4.4.2.1 Research objective and research question

Offering custom tailored buildings at reasonable costs has been a growing concern to many construction companies. As the literature review discussed in Section 3.1 shows, a promising approach adapted by operations management and design theory regards individual building projects as the adjustment and recombination of components and processes from a set of predefined platforms, while CSs assure feasible building solutions. Based on the developed understanding of how to plan and implement CSs, the aim of this paper is to explore the development of a platform-based project execution in the industrialised construction sector, with a focus on systematically balancing for cost and value. The obtained results would enhance the current understanding of how architecture design influences the specification process. In particular, it investigates the aspect of research question *RQ2.1* (RQ2.1: How can postponing the customer order decoupling point be enabled and how does it affect the specification process of ETO companies? ) based on the industrial construction industry.

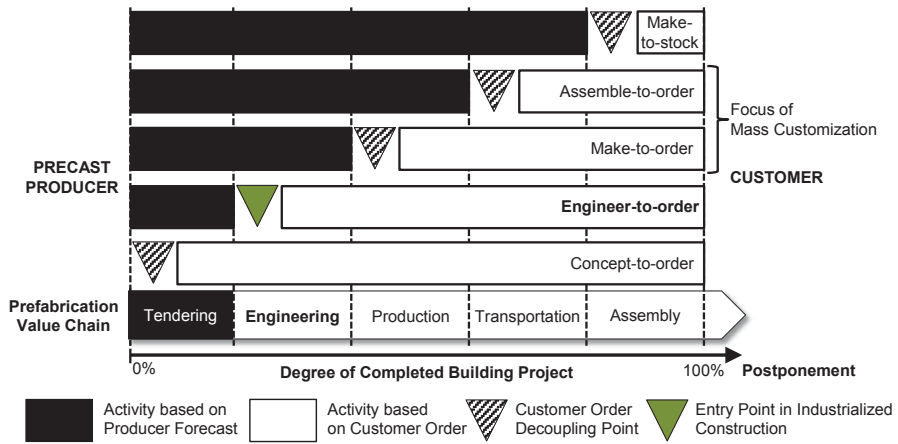
### 4.4.2.2 Research contribution

#### ***Manufacturing control and customization in industrialized construction***

The specific differences in manufacturing determining the placement of the customer order decoupling point can be illustrated on the construction industry. Research in construction has a long tradition in comparing and adapting related approaches from other industry sectors, like car production. Several authors have investigated the potential of such cross-industry learning, where significant benefits on industrialised housing could be proven (Barlow *et al.*, 2003). A key lesson from the automotive industry is the ability to provide a higher degree of customisation without compromising lead times, quality and costs (Parry and Graves, 2008). What became known as mass customization aims at using CSs, adjustable product structures, flexible processes and adaptive organisations around a predefined set of platforms to efficiently offer custom-tailored products (Su *et al.*, 2005). To explore the potential for platforms, manufacturing companies are classified according to the customer order decoupling point (CODP), i.e. the degree the manufacturing set-up is customer-independent and based on forecast or order-related and connected to a specific sale (Sharman, 1984).

Wikner and Rudberg (2005) categorised the most commonly mentioned strategies throughout literature as engineer-to-order (ETO), make-to-order (MTO), assemble-to-order (ATO), and make-to-stock (MTS). In the context of construction, concept-to-order (CTO) is in addition used to describe a situation in which a customer is strongly involved already at the early conceptual phase of a building project (Winch, 2003). Taking the example of a building, by engaging with e.g. the architect, in a CTO situation the customer then actively shapes the conceptual building scheme from the beginning, without in particular basing his ideas on a predefined structural or feasibility concerns (Mora *et al.*, 2008). Empirical examples can be found in one-off projects, where uniqueness of design is more important than productivity or functionality (Hobday, 2000). In a MTS strategy, on the other hand, the customer enters the process at a very late stage of its value creation. This strategy makes use of market forecasts to convert raw materials and components all the way to final standard products in accordance to expected customer demands. Between those two categories there

are MTO and ATO firms which allow a certain degree of customisation based on the standardisation level of their products, like for example the previously mentioned car manufacturers.



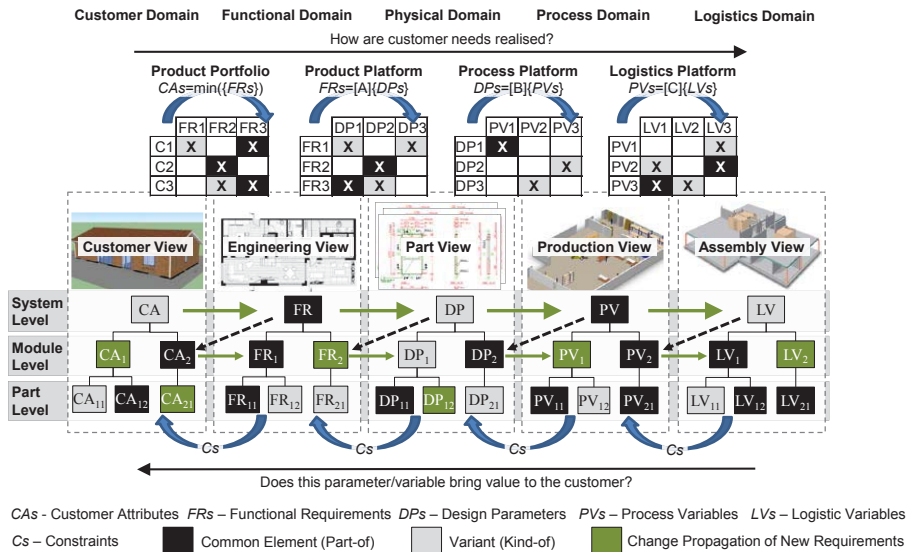
**Figure 4-14: The CODP model in relation to the value chain of a precast manufacturer**

In relation to the CODP, the precast supplier can be classified as an ETO manufacturer providing industrialised building systems (Zabihi et al., 2013). As a common characteristic for ETO firms, the value chain consists of a non-physical stage involving marketing, tendering and engineering activities and a physical stage which concerns production, transportation and on-site assembly (Bertrand and Muntslag, 1993). The schematic representation in Figure 4-14 indicates how the customer enters the engineering phase of the value chain after completing the tendering process for a project. Starting from there, all subsequent phases including producing the concrete elements, shipping and assembling them on the construction site, can be directly related to a particular customer or client order.

### Platform modelling framework for building projects

Figure 4-15 illustrates a holistic approach to product family design through platforms throughout the value chain of a building project. The framework comprises five domains; customer, functional, physical, process, and logistics domain. The customer domain involves the development of customer insight, where marketing techniques are used to determine customer attributes (CAs), i.e. requirements in relation to the market (Meyer and Lehnerd, 1997). Apart from requirements directly coming from the customer, there are a number of stakeholder requirements and governmental regulations that need to be fulfilled as well (Stevens and Martin, 1995). For ETO firms the nature of the requirements tends to be specific and technical (Rahim and Baksh, 2003). In the building sector they are often related to the building design and its different levels of details (Kiviniemi, 2005). As building regulations evolve, house builders and off-site manufacturers have to keep compliance and quickly adapt to new demands (Pan et al., 2007). Once identified, common requirements can be grouped together to form consistent value propositions for different market segments and to grade the impact the stakeholders have on them (Simpson et al., 2011). CAs are then converted into a minimum set of functional requirements (FRs) in the functional domain as  $CAs = \min(\{FRs\})$ . Here architects traditionally develop building concepts from the customer information in an architectural design, based on existing industry norms and standards and available product technologies. The architectural design includes overall parameters of a building and architectural preferences on e.g. materials, shapes and styles, or increased energy efficiency. In platform terms, this mapping constitutes the definition of a

product portfolio with a number of product families through which common practices of order configuration and sales automation with CSs are performed (Jiao, Simpson, et al., 2007).



**Figure 4-15: Holistic view on platforms in industrialised construction**  
Source: Adapted from (Jiao, Simpson, et al., 2007)

Mapping the relationships and interfaces of FRs to design parameters (DPs) is done in the physical domain and encompasses the definition of a product architecture as  $FR_s = [A]\{DP_s\}$  (Suh, 2001). Engineers transfer the initial design intent of the architect into a structural model with the objective to create feasible structure solutions, while referring to given architectural patterns and constraints. Such decisions are mostly based on the engineer's knowledge and experience of the realisation of the design intents on a given situation. With the structural analysis and the determination of the building behaviour of the preliminary design, the design focus changes from the innovative design intent of the conceptual design to a design task on a routine basis (Mora et al., 2008). A process architecture can be defined accordingly as the mapping of the DPs to process variables (PVs) in form of  $DP_s = [B]\{PV_s\}$  and logistics variables (LVs) as  $PV_s = [C]\{LV_s\}$  respectively. The last two domains traditionally involve the creation of common manufacturing processes, production technologies and distribution networks (Meyer and Lehnerd, 1997). Common production tools, machines, transportation resources and assembly methods can be used to reduce manufacturing set-up risks and to reuse proven production and assembly processes (Sawhney, 1998). From a precast perspective, the main concern is the transformation of design specifications of a building into physical precast elements and their subsequent on-site assembly.

In an ETO situation developing well-functioning relationships among teams and team members is particularly important. Sales, engineering and production activities are traditionally rarely standardised and rely on specific skills and craftsmanship. Extended coordination mechanisms are therefore used to balance product specifications with engineering and production capabilities for all upcoming orders (Konijnendijk, 1994). With the employment of stable teams within each stage of the value creation of a building, the precast producer can expect to benefit from economies of scope. The ability to produce and deliver the created building designs results in constraints, (Cs) which have an upstream effect on the foregoing domains. Precast elements, for example, need to be lifted and assembled at the

construction site. Build-in lifting brackets and mechanisms for assembly have to be designed and cast in place at the foregoing steps of the product realisation process.

Modelling platforms from different perspectives through the so called views facilitate the consideration of all five domains of a building project (Jiao and Tseng, 1999). As indicated in Figure 4-15: Holistic view on platforms in industrialised construction, generic modelling notations are commonly used to represent hierarchies, commonalties (Part-of structure), alternative varieties (Kind-of structure), and ranges (Jiao and Tseng, 1999). Change propagation effects from newly identified building requirements can then directly be seen within the system (Clarkson et al., 2004). The hierarchical classification of materials, parts, components and sub-assemblies represents the product structure (Do et al., 2002), and is consistent with the common definition for bill of material (BOM) (Garwood, 1988). The different perspectives and relationships are modelled with the same notation, while their interrelations are mapped through direct connections and constraints for configuration. Most generic modelling approaches follow the basic principles of object oriented modelling using the Unified Modelling Language (UML) (Felfernig et al., 2000). With their help, even complex product architectures, such as for ETO products can be created (Brière-Côté et al., 2010). Today existing product lifecycle management (PLM) solutions obtain the same object-oriented hierarchical structure of a product (Mesihovic et al., 2004). The overview of product structures with many component interrelations may be maintained with matrix-based modelling methods (Steward, 1981). The elements of such matrixes are simply listed in columns and rows and connections are made through the matching cells. Over the years, many related modelling methods and tools have been proposed in academia. With their relatively simple notation, Design Structure Matrixes (DSMs) have for example been developed to assess, reorganise, and cluster relationships between functional or physical elements (Eppinger et al., 1994). The methods have been applied on a number of product examples spanning from commercial to industrial products. To represent hierarchies of common and distinct elements in ETO platform designs, the matrix-based models are to be combined with the generic modelling techniques.

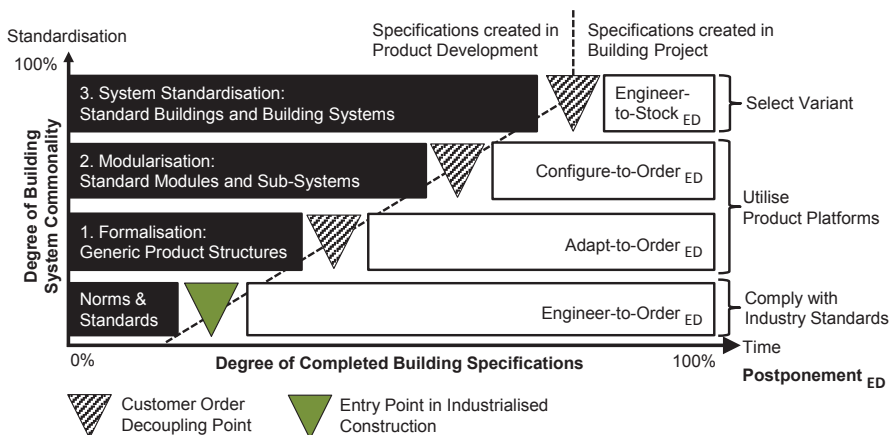
### ***Robust design effects in engineering***

ETO firms are by definition strongly concerned with engineering activities and how they are to be carried out in combination with manufacturing (Konijnendijk, 1994). To achieve the benefits from the use of platforms, they have to postpone the CODP to a later stage of the value chain, or in other words they have to accept a higher degree of predefinition of the subsequent tasks. Wikner and Rudberg (2005) point out the two-dimensional character of postponement for ETO firms. Apart from the production dimension, postponing the CODP can be seen from the engineering perspective as well. Based on contributions identified in literature, the authors conceptualise the extended two-dimensional framework of the CODP and further describe the characteristics of a possible engineering-production mix in terms of postponement. Precast manufacturers are traditionally characterised as being engineer-to-order in the engineering dimension (ETO<sub>ED</sub>). They use the majority of their engineering resources for making building specifications on individual projects, while complying with industry specific standards and norms. Their products obtain a low number of commonality, as the solution space communicated to their customers contains no explicitly formulated boundaries in form of e.g. catalogues from the beginning. Figure 4-16 depicts the link between the degree of standardisation from a building system perspective and its potential impact on placing the CODP in engineering.

The lowest level of system standardisation (*level 1*), i.e. formalisation, targets the part and component level. From a precast perspective such components are for example represented by different forms and dimensions of iron bars, insulation materials, concrete recipes etc. The formalisation process includes the creation of a formal product family model containing generic product structures of the domains. Through product development, precast manufacturers need to agree on a common solution space for their product families,

where for example, possible precast element dimensions, load bearing capacity, dimension and placement of recesses, or different materials and surfaces are mapped. The objective of this stage is to make an explicit documentation of possible variations, calculations and restrictions for a given family, without necessarily reducing the functionality and respectively the variety given to customers. By formalising the product portfolio, the precast producer is able to reuse the product knowledge on each building project more systematically and adapt-to-order (ATO<sub>ED</sub>) the building specifications within the boundaries of the established solution space. KBE systems can then be employed to integrate the formalised technical product knowledge with the order fulfilment process and thus to promote gains from knowledge reuse and sharing (Stokes, 2001). In literature, several attempts to increase organisational capabilities within the construction sector through IT system support can be observed, for example: Udeaja et al. (2008), Rezgui (2001) and Nitithamyong and Skibniewski (2004). In an ATO situation so-called product CSs are used to streamline the sales and quotation process of customised goods in satisfying the term  $CA_s = \min(\{FR_s\})$  (Salvador and Forza, 2004). For ETO sectors such systems are moreover helpful to partly automate some of the subsequent engineering activities in assistance of  $FR_s = [A]/\{DP_s\}$  (Hvam et al., 2008). However, comparable achievements in coordinating the specification process in construction have not yet been reported.

In level 2 standardisation engineers may define a standard set of building modules or subsystem variants, like different types of facades, which can be commonly used within the precast families. The various modules and sub-systems would be reconfigured for each building project through a configure-to-order (CTO<sub>ED</sub>) approach. At level 3 standardisation finally refers to the development of entire standardised buildings or building systems, as e.g. a pre-defined set of walls to an entire house type. Since all product specifications for a building project are defined prior to the actual customer order, this strategy can be characterised as engineer-to-stock (ETS<sub>ED</sub>). Companies offering houses from a type house catalogue are a good example for an ETS<sub>ED</sub> strategy. The focus of using product platforms for mass customizing buildings lies between the continuum of ETO<sub>ED</sub> and ETS<sub>ED</sub>, where the precast manufacturer accepts a certain level of product adjustments on a module or part level in the design based on individual customer needs. Empirical examples within related industries, such as for mass customized timber houses, can for example be found in the Japanese housing market as discussed by Gann (1996).



**Figure 4-16: Leveraging the platform strategy through different decoupling points in engineering**

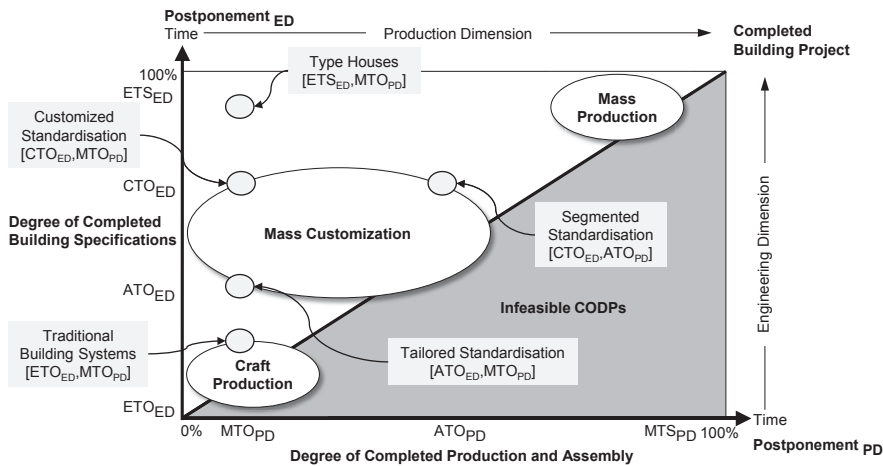
Source: After (Hvam et al., 2008, p. 28)



***Combined robust design effects on the precast value chain***

As argued by Wikner and Rudberg (2005), several feasible interrelations of a combined engineering-production CODP-mix can be defined. Figure 4-16 illustrates how two-dimensional placement of the CODP can be applied to the building industry. Precast firms are traditionally utilising a craft production approach in form of  $ETO_{ED}$  combined with a make-to-order in the production dimension strategy ( $MTO_{PD}$ ), or in short a  $[ETO_{ED}, MTO_{PD}]$  strategy. In contrast, the  $ETS_{ED}$  strategy of type house providers is used in combination with the MTO production dimension as  $[ETS_{ED}, MTO_{PD}]$ . Even though for type houses all building specifications are already defined in the product development phase, the production of walls for example, would not start unless an order has been placed. According to the CODP definition, mass produced buildings with a  $[ETS_{ED}, MTS_{PD}]$  strategy would be created entirely based on forecasts, in other words they would be pushed to the market without any consideration from customers or clients. As displayed in Figure 4-17, the mass customization area covers the remaining mix of feasible engineering and production mix approaches. The Japanese timber house market can be used as an analogy for the empirical evidence of the proposed strategies. Sekisui House, for example, follows a so-called “tailored standardisation” approach with an  $[ATO_{ED}, MTO_{PD}]$  strategy. The company uses standard components which are mainly produced on demand and adopted to customer requirements. The on-site assembly is done by specially trained subcontractors (Gann, 1996).

Another mass customization example in construction is represented by Sekisui Heim (Barlow *et al.*, 2003). The company makes use of a “standardised customisation” strategy through an  $[CTO_{ED}, MTO_{PD}]$  approach, where standard modular steel- and timber-frames around rooms are created off-site only few days before delivery. The modules are then directly shipped to the building sites for further assembly. An example for a  $[CTO_{ED}, ATO_{PD}]$  strategy can be found on Toyota Homes. The company utilises a so-called “segmented standardisation” approach, which is comparable to Toyota’s car production. Modular units are produced based on forecasts without any significant input from customers. Customisation is then performed in the on-site assembly process, where modules are recombined and adjusted to particular housing needs. All three approaches make use of process and logistics platforms to significantly reduce the time and resources for manufacturing and on-site assembly. According to Gann (1996), having modules requires 50% less labour cost for the on-site assembly process. At the same time up to 55% assembly lead time compared to traditional pre-fabricated panel houses or up to 67% compared to a carpenter-built building are being saved. Therefore, the companies are able to combine a high degree of tailoring from their customers and clients with a stable delivery quality. To achieve the required productivity, the individual postponement strategies are further supported by innovative off-site manufacturing practices, which are comparable to assembly lines car manufacturers.

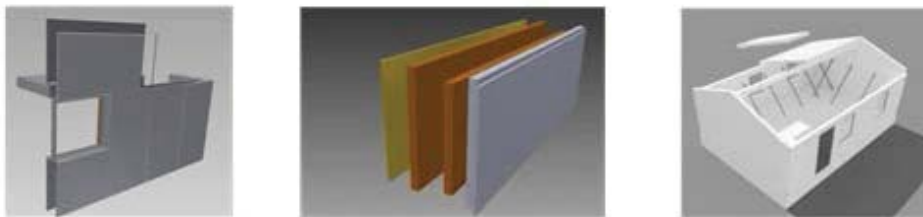


**Figure 4-17: Leveraging the platform strategy through a two-dimensional placement of decoupling points**

Source: Adapted from (Rudberg and Wikner, 2004)

### Empirical analysis and results

The development of the HPC product portfolio was initiated in 2010. Working on new concrete recipes, the organisation intuitively realised that many of the building challenges in developed and developing markets could potentially be addressed by using HPC as an alternative to e.g. the traditional concrete, plaster or wood materials already existing on the market. The company made an initial investigation on a number of markets both in Northern Europe as well as in developing markets in the southern part of Africa from a customer perspective. A series of CAs where formally listed, grouped and graded. A five scale approach as defined by Martin and Ishii (2002) with 1) least important and 5) very important was used to derive general requirements from the CAs into concrete DPs. Moreover, the CAs' potential for propagation of changes within the system was graded based on the stakeholders' subjective preferences (Clarkson et al., 2004). From the initial grouping of the requirements, three different distinct product families could be formed: a High-End, a Re-Insulation and a Low-End building system (Figure 4-18).

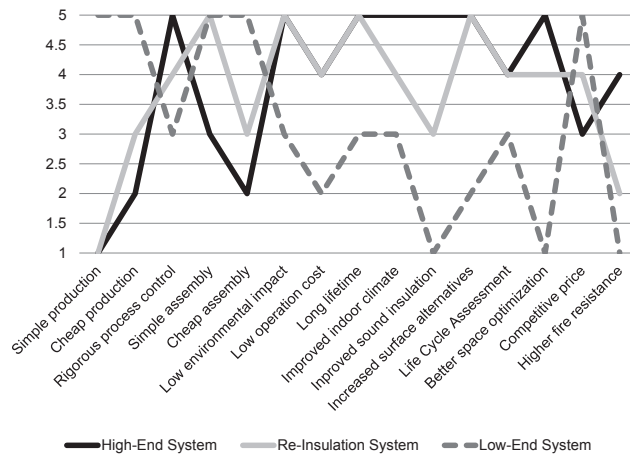


**Figure 4-18: High performance concrete product portfolio: Re-Insulation, High-End and Low-End sys-tem**

Figure 4-19 displays the high-level list of CAs, the characteristic value proposition for each product family where the product family names indicate the intended market application. The design of the HPC High-End solution is closer positioned to the traditional elements. It targets the high-end market segment for customers who are concerned with buildings that obtain a unique surface design and aesthetics, better insulation, increased space optimisa-



tion as well as reduced CO2 emission. The Re-Insulation system aims at competing with established products using metal or wood for re-insulating existing buildings. It utilises the same HPC material for offering Re-Insulation panels that, compared to existing solutions, have a longer life-time, an improved surface design and variety and low operation cost, which are easy and cheap to assemble. The third building system targets the low-end market segment of shack dwellers, which are predominately to be found in developing markets. Based on the same HPC technology, this solution provides stable and long-lasting buildings with a reasonable quality at a competitive price and thus suggests a fundamental alternative to existing low-end housing today. Due to the special requirements for this market segment (Ofori, 2007), the Low-End system is emphasising a strong focus on using local and often unskilled labour, cheap and simple production with predominantly local material and a simple and quick on-site assembly. This explicit value proposition allowed the engineers to focus on aspects within each building system which generate a direct value to the customer, while limiting the non-value adding activities.



**Figure 4-19: Value proposition of the three product families with evaluated customer attributes**

With the initial value definition for each product family, the design of the building systems was created in a close collaboration between architects and engineers. To compare the similarities and differences between the families, the traditional precast products are used as threshold values representing the current market norms for the industry. The result of the comparison is summarised in Table 4-10, where for each product family the heuristic approach to platforms has been applied. The different views of the building system were modelled according to the generic modelling methods introduced by Hvam *et al.* (2008), while intra-domain matrixes were used to connect views.

#### ***The product platforms used in the high-performance concrete portfolio***

The High-End HPC system consists of sandwich elements and their connection to each other and to other building systems, such as to foundation or ceiling. From an engineering perspective, the modified concrete recipe of the elements obtains a number of functional advantages compared to the traditional concrete elements, which facilitate fulfilling the objective of  $CAs = \min(\{FRs\})$ . In addition to an altered concrete material, a longer building lifetime has been obtained through a new joining system made from stainless steel. From a part view, with the High-End system the company focused on the value adding variety on the component level, while preserving the flexibility to meet all customer demands within the target market segment. Compared to traditional concrete elements, the High-End system

uses fewer variants for reinforcing, insulating and connecting the sandwich elements, resulting in an overall higher part commonality of the system.

The Re-Insulating system utilises the same HPC material as the High-End solution. To conform to the requirements (FRs) of the re-insulating market, several additional DPs have been added. Instead of having a back plate made from concrete, a second layer of insulation material has been attached to the elements. A new mounting system ensures the fixation of the elements to the existing building, while a simpler jointing solution made out of stainless steel has been developed to seal the surface of the system. The Re-Insulation elements consist of a limited number of modules coming in different sizes. To ensure a high degree of flexibility, all modules use the same mounting and jointing system and can be combined and exchanged without affecting each other. Since the HPC material is more costly compared to the competitive products on the market made out of wood or metal, to reduce the cost of the each element, unnecessary variety of the remaining parts has been lowered considerably. However, compared to the existing market standards, the additional variety of surfaces ensures the high aesthetic value of the overall re-insulation. For the Low-End system on the other hand flexibility is less important than price. As all HPC building systems mainly share the same raw materials, the company must focus on standardising the Low-End system as much as possible. It uses two different element types, roofs and surfaces in combination with common components to create entire buildings at a competitive price. The shape and size of the buildings can be modified, as elements can be moved, recombined or additional ones can be attached.

**Table 4-10: Overview of the platform strategy of the high performance concrete portfolio in relation to traditional precast elements**

Dimension	Traditional Precast	High-End System	Re-Insulation System	Low-End System
<b>Product Portfolio</b>	Market average requirements for aesthetic, insulation, space optimisation, lifetime and environment	High requirements for aesthetic, insulation, space optimisation, lifetime, quality and environment; low requirements on price, easy production and assembly	High requirements for insulation, lifetime and assembly and space optimisation; moderate requirements for aesthetic and price	High requirements for surface design, easy and cheap production and assembly; moderate requirements on lifetime and environment; low requirements for aesthetic, insulation and space optimisation
<b>Product Platform Engineering View</b>	Traditional concrete recipe, market norms for strength, load-bearing capacity, heat and sound insulation, lifting	High performance concrete, increased capabilities in strength, load-bearing capacity, lifetime, heat and sound insulation, reduced CO2 emission; redesigned joining system	High performance concrete with the same characteristics as the high-end system; redesigned insulation, joining and mounting system	High performance concrete with the same characteristics as the high-end system; redesigned joining and mounting system to other buildings
<b>Part View</b>	Part commonality at market norms; iron mesh with limited variety, multiple shear connectors, insulation materials, reinforcement, recesses, concrete recipes and surfaces	Increased commonality in element dimensions, common iron mesh, two shear connectors, two insulation materials, limited reinforcement, common concrete recipe, alternative additional surfaces and joining elements	Few common element dimensions, common fibre mesh, common mounting system to walls, two insulation materials, common reinforcement and concrete recipe, few surfaces, common joining elements	Two common element dimensions, common fibre mesh, shear connector, insulation material, reinforcement, recesses, and concrete recipe, two surfaces and roofs, common joining elements
<b>IT Support</b>	No specification process support	No specification process support	No specification process support	No specification process support
<b>Process Platform Production View</b>	Flexible processes, little mould commonality	Flexible processes, little mould commonality	Limited process flexibility, high mould commonality	Limited process flexibility, very high mould commonality
<b>Team Members</b>	Unstable relationships	Stable relationships	Stable relationships	Stable relationships
<b>Handover Process</b>	Little quality control, no formal handover procedures	Pre-defined end deliveries demanding for well defined sub-delivery for each handover	Pre-defined end deliveries demanding for well defined sub-delivery for each handover	Pre-defined end deliveries with less strict sub-delivery
<b>IT Support</b>	Inconsistent data collection, no systematic learning	Centralised documentation, i.e. measurements, observations, sensors, tagging, quality control, central database	Centralised documentation, i.e. measurements, observations, sensors, tagging, quality control, central database	Centralised documentation, optional quality control
<b>Continuous Improvement</b>	Long-term cycles	Short-term cycles	Short-term cycles	Md-term cycles
<b>Logistics Platform Transportation</b>	Little space utilisation due to weight restrictions for trucks	High space utilisation due to 50% less volume and 70 % less weight	High space utilisation, comparable to re-insulation market norms	Maximum space utilisation with smaller trucks, due to 80-95% less volume and weight
<b>Assembly View</b>	Crane size and assembly process according to market norms	Smaller cranes due to reduced element weight, higher requirements during assembly process	Smaller cranes due to reduced element weight, fast assembly process with standardized tooling, no scaffolds	Small cranes, more than 50% less assembly time with standardized tooling
<b>Team Members</b>	Unstable relationships	Stable relationships	Stable relationships	Stable relationships
<b>Handover Process</b>	Little quality control, no formal handover procedures	Pre-defined end deliveries demanding for well defined sub-delivery for each handover	Pre-defined end deliveries demanding for well defined sub-delivery for each handover	Pre-defined end deliveries with less strict sub-delivery
<b>Continuous Improvement</b>	Long-term cycles	Short-term cycles	Short-term cycles	Md-term cycles
<b>Postponement Strategy</b>	ETOED, MTOFO	ATOED, MTOFO	CTOED, MTOFO	CTOED, MTOFO

### *The process platforms used in the high-performance concrete portfolio*

In construction terms the HPC product platforms exhibit a rather radical degree of redesign compared to the traditional concrete elements. From a production perspective this difference is less obvious, as all three HPC building systems mainly go through the same production steps as the traditional elements. Yet, a cost and time advantage is achieved through reusing already existing production facilities, machineries, equipment and labour. Additional benefits arise with the higher degree of part and module commonality of the HPC portfolio, resulting in less flexible but at the same time more reliable and stable production steps. While for the High-End solution the effect from increased part commonality is smaller, the Re-Insulation and Low-End elements strongly benefit from the standardisation attempts on the module level. Through the limited variety in dimensions, the company reuses a set of standardised moulds for casting and recesses made out of steel, thereby reducing waste and the need for resetting the production. Furthermore, the thinner dimensions and sharper edges of the HPC elements result in smaller production tolerances. To meet the increased quality demands when working with HPC material, stable and well trained teams have been created along with well-defined handover procedures for process deliveries. The high quality standards are ensured with additional IT support for measuring, monitoring and tracking the entire production. A central data base has been installed to collect and evaluate the acquired information. This constant quality control has led to shorter continuous improvement cycles of the HPC products and the way how they are produced.

### ***The logistics platforms used in the high-performance concrete portfolio***

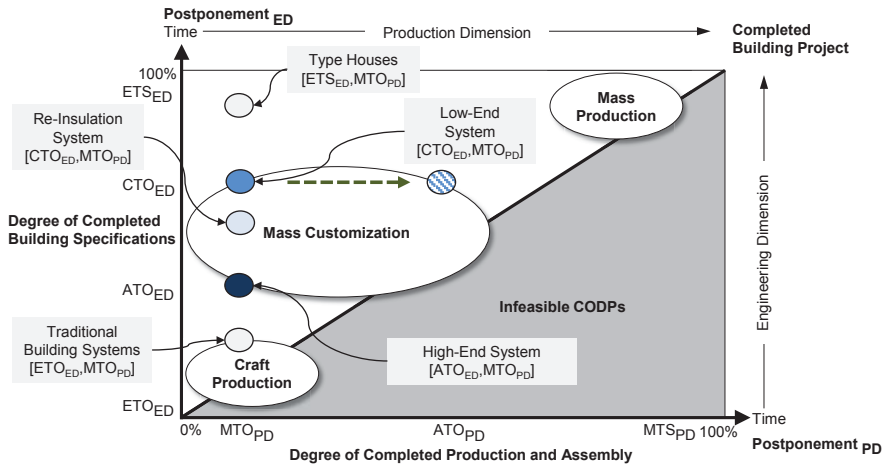
A major advantage of using HPC instead of traditional concrete recipes is the reduced dimensions and weight of the elements. Transportation costs of the elements are typically responsible for 10% of the cost of the entire building system. Therefore reducing the costs of shipping the elements can have a big impact on the overall profitability of the building projects. This effect is exemplified on the High-End system. Here, the HPC sandwich elements have 50% less volume and up 70% less weight compared to traditional precast elements. In result the company is able to better utilise the space of the trucks that are used for shipping and have considerable savings during assembly, which would otherwise be restricted by the weight of the elements. In developing markets the reduced volume and weight of the Low-End building system even accounts for 80-95%. Smaller and lighter elements in turn make it possible to transport the elements with smaller trucks even through rural and unpaved areas. Another factor contributing to a lower price is that fewer variants of the product are offered based on the Low-End product platform. From an assembly perspective the volume and weight reduction of the HPC portfolio means that the company can operate with smaller and cheaper cranes at the building site. Moreover, with the Re-Insulation and Low-End solution, the case company has introduced a new fast and simple assembly process, where standardised tooling is utilised for the entire on-site work. Apart from the benefits coming from smaller and lighter elements and standardised processes, a strong emphasis is being set on the employees and the quality of delivery. Comparable with the process platforms, stable and specialised teams are making sure that the predefined deliveries and all handover processes are being kept. Besides, the increased transparency during assembly leads to shorter feedback cycles; allowing the company to continuously improve their procedures in shorter terms.

### ***Platform effects in the high-performance portfolio***

The platform analysis of the HPC portfolio demonstrates the potential advantage of focusing on the right balance between commonality and distinctiveness within each view of a product family. For the case company an increased reuse of building specifications, machineries, tools and processes created in the development phase resulted in a higher degree of commonality along the value chain of a building project. Compared to a traditional precast project, an increased reuse capitalises in the ability to delay the differentiating activities of each project. Figure 4-20 depicts the postponement strategy of the three HPC product families. Depending on the intended positioning in the market, each product family is using the platforms to a degree, which allows placing the two-dimensional CODP according to the optimum cost-value relation. A traditional building project at the case company today requires in average three hours of engineering work per concrete element, once the detailed design of a building has been finalised. Having invested in formalising its offerings to the market, the High-End system on the other hand adapts systematically the building specification created during product development to the individual requirements of a project with an  $[ATO_{ED}, MTO_{PD}]$  strategy. The firm operates with the  $ATO_{ED}$  strategy within the boundaries of the assigned solution space in engineering, allowing for a higher level of flexibility in the subsequent production and assembly. While ensuring the desired delivery quality, the company strives in gaining economies of time throughout the specification process of the building, saving up to 20% of engineering time for completing the building specifications. The effect of increased reuse of building specifications is even stronger for the Re-Insulation and the Low-End system, where up to 80% of the overall engineering time is being economised. Both systems utilise a  $[CTO_{ED}, MTO_{PD}]$  approach, in which the benefits of having standardised modules take effect already at the conceptual design phase of the project. Even though formal product architectures have been established, at the time of the study the case company has not invested in establishing a CS for any of their products. With the planned implementation of IT, additional positive lead time effects in engineering are expected. However, the observations indicate that the successful use of a CS support depends on how well

the organizational changes are being implemented, rather than if such a system is capable of assisting the specification process.

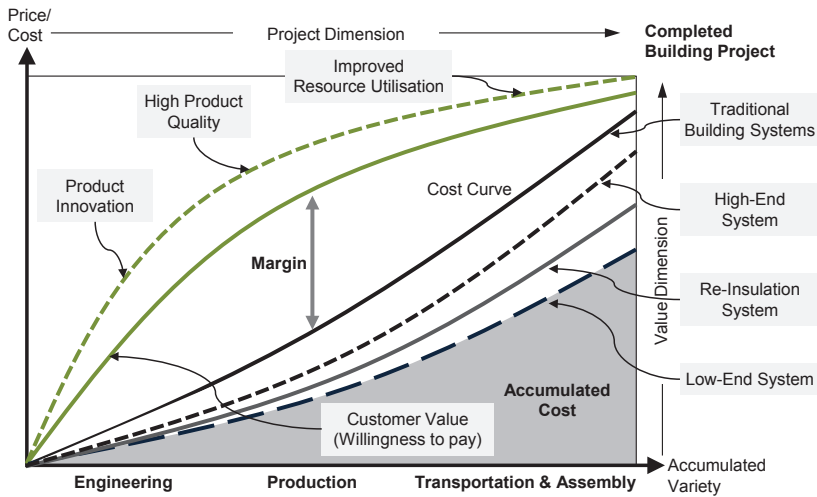
The higher level of commonality along the entire life cycle of the building project directs to additional reductions of lead times within production and on-site assembly. The additional benefits from using the platforms can be exemplified on the Low-End system, where the standardised production processes report a 30-50% lead time reduction. The redefined on-site assembly allows the company to use standardised tooling combined with lighter and smaller elements to assemble a single family building with three workers and one single tool in merely seven hours after having cast the foundation. With the ability to deliver quick and cheap housing, the company aims at directly addressing the growing housing demand in developing regions. As indicated in Figure 4-20, once access to new markets has been gained, scale-up programs are planned to increase the productivity of factories. By moving from a  $[CTO_{ED}, MTO_{PD}]$  towards an IKEA model  $[CTO_{ED}, ATO_{PD}]$  strategy (Li, Guo, et al., 2011), the different wall elements can then be produced based on a forecast, reducing the delivery time of the building to the lead time of transportation and assembly. While staying within the boundaries of the building system, each customer is then able to order his configured house, based on an individual combination of the elements.



**Figure 4-20: Platform leverage strategies for the HPC portfolio**

Apart from economies of time, with the platform strategies the company is bridging the paradigm of delivering the optimum cost-value relation for each HPC product family. Figure 4-21 illustrates the impact the utilised platforms have on the accumulated cost of the case company throughout a building project. While the higher flexibility of the High-End system results in a relatively high cost structure which is close to the traditional building systems, it focuses on generating higher margins through a selective value proposition. An increase in material costs is compensated with savings in engineering, transportation and assembly, while the improved aesthetics and material properties add additional value to customers. Similar to the platform strategy of car manufacturers (Proff, 2000), as discussed previously the Re-Insulation and Low-End systems benefit from adapting product innovation, production technologies as well as better utilised resources during transportation and assembly of the High-End system to constantly improve their platforms. Furthermore, being more concerned with offering competitive prices, the two families focus on reusing their assets along building projects, where non-value adding variety is reduced to a minimum. This enforced simplicity for example lowers the cost of a Low-End building to price points that are compatible to slack dwellers in development markets, yet using comparable materials and product quality as the High-End system. Finally, the overall platform strategy of the company has

resulted in a number of patterns, which are used to secure their competitive advantage from the illustrated product and production innovations.



**Figure 4-21: Economic implication of the HPC platforms in the case company**

#### 4.4.2.3 Conclusion

Research in construction has long been focusing on adapting concepts and methods from other industries such as the automotive industry to bring forward industrialisation and to reach higher productivity levels. While the accommodation of lean principles has received much attention, fundamental methods for ensuring an efficient customisation of buildings have mainly been neglected. Mass customisation aims at bridging this gap of delivering customised products at near mass production efficiency. Successful mass customizers to be found in industry apply platforms as a means to acquire economies of scale while maintaining adjustable product structures, flexible processes and adaptive organisations. In addition they use product CSs around their platforms in support of their specification processes. Scholars approaching this topic have to adapt the two principles to the ETO situation in construction and to present practical guidelines for their implementation.

In addressing the two issues, this paper has presented a holistic view of platforms as a framework for understanding how mass customizing building projects is being facilitated in general. The study uses the precast sector as a representative industry to formalise the value chain of a building project in relation to the different manufacturing strategies according to the CODP. By drawing upon theory in platform development, the application of a product, process and logistics platform has been explained on the example of a building project. To create the right balance between commonality and distinctiveness, relationships between the platform domains as well as the connection to market requirements have been expressed through generic and matrix-based modelling methods. Then, the two-dimensional postponement of the CODP has been employed to synthesise the relevance of using CSs and to conceptualise the operational effects of platforms throughout the lifetime of a building project. Likewise, a cost-value concept has been introduced to explain the related economic implications.

The paper employs a mixed-method research design, from both qualitative and quantitative sources, to collect evidence for the holistic view on platforms within the precast sector and to validate the developed framework. The applied methodology facilitated the in-depth exploration of how practitioners from the industry take up the platform concept,

what challenges they face, as well as what benefits they realise. In the subsequent analysis, three distinct platform strategies from a precast manufacturer were compared to the otherwise traditional building projects. Each strategy was related to the previously introduced framework and discussed according to both its operational as well as economic implications. The obtained results demonstrated strong incentives for implementing several feasible platform constructs within the precast industry. Moreover, the benefits from integrating CSs throughout the specification process of buildings were conceptually elaborated, for which an enormous potential for future research has been recognized. Pragmatically, the findings suggest that utilising platforms does not necessarily imply sacrificing design flexibility and customer value respectively in favour of efficiency, but rather involves the creation of an optimum cost-value relation for the target market segment. This case study approach admittedly implies certain limitations with respect to generalisability and repeatability of the research. The increasing maturity level of the industry entails that essentially any major precast manufacturer operating in developed markets obtains few universal capabilities with respect to its value chain (Li et al., 2014), and may hence be used as a basic representative example to test the introduced framework. On the other hand, as demonstrated a consistent platform approach requires a certain level of development effort to obtain the discussed two-dimensional postponed strategy. This innovation process has to be performed independently from any particular building project and involves the application of the discussed modelling methods (Brière-Côté et al., 2010; Meyer and Lehnerd, 1997; Suh, 2001), which is however traditionally rarely the case within the building sector (Gambatese and Hallowell, 2011). Consequently, further empirically-grounded research on a variety of building systems is needed to better understand the complementary effects of platform modelling, CS support and postponement, as a result of the introduced framework. This would increase the interest in mass customization within house building and may further lead to a wider acceptance of the presented methods.

Thereby, this study helped answering RQ2.1.

**RQ2.1:** How can postponing the customer order decoupling point be enabled and how does it affect the specification process of ETO companies?





#### 4.4.3 Paper H: Method refinement

**Title:**                **Product platform considerations on a project that develops sustainable low-cost housing for townships**

Published in:    CIB World Building Congress 2013, Brisbane, Australia

Case study:        #3

##### 4.4.3.1 Research objective and research question

This study is a follow up of Paper G presented in Section 4.4.2. It refines the understanding from the initially developed platform concept with respect to how the architecture development of one product family can be used as a learning point for other families. The results improve the understanding for answering *RQ3.2* and *RQ3.3*.

##### 4.4.3.2 Research contribution

###### ***Research background***

It is estimated that about 1.6 billion people around the world live in sub-standard housing and over 100 million are homeless. If no serious action is taken the number of slum dwellers is expected to rise from one billion people today to two billion within the next 30 years (Habitat for Humanity, 2013). This leaves many developing countries with a problem that is hard for them to overcome. South Africa is one of the countries that are taking action, as it tries to solve its housing problem by means of a centrally planned housing programme. Through this programme, since 1994 more than 2.3 million housing units have been made available to nearly 11 million people, where in 2010 alone about 219.000 housing units have been made. The goal for the coming years is to create 220.000 housing units a year. Despite such a tremendous number of erected units, the housing backlog has grown from 1.5 million units in 1994 to 2.1 million units today. This means that 12 million South Africans – a quarter of the population – are still in need of a better shelter. Inspired by the housing programme of the South African government, the case company described in this article examined whether and how it would be possible to contribute to the housing problem of developing nations with its knowledge and technology.

Studying the situation resulted in the main proposition that creating and introducing a platform concept to low-cost markets would support both, developing countries in overcoming their housing problem in an effective manner, and construction companies to improve their performance in the domestic markets. To this end, this article in particular addresses the following aspects:

- a) It is possible and beneficial to develop a low-cost product family that can be used for making low-cost houses
- b) It is possible to make several variants of houses based on that low-cost product family
- c) The new knowledge gained by developing and implementing a product platform for low-cost housing will contribute to improved efficiency and reduced prices in the high-end family.

###### ***The low-cost product family***

When developing the low-cost product family and building the houses, a series of key observations, that are further grouped and described in detail, has been made.

- On a conceptual level there were many elements that could be re-used from the high-end product family; e.g. the basic methodology when describing a platform structure and how to phrase requirements. Previously, there was not much reuse between the two other product families

- A solution for the design of the HPC elements has been found that required only few tools for assembly. Buildings can even be assembled without using power tools, since stable electricity sometimes is absent on some building sites. An assembly where only few tools are needed also makes teaching of staff easier and leaves less room for error
- Even though unskilled labour and no high technology production are being used, many houses can be produced during a year. This is due to the production of only few different kinds of elements, which are strongly standardised and can be used across the product variants. Using unskilled labour and no high technology also changes the description of requirements from being database and specification focused to being expressed in photographs and drawings wherever possible
- Once the HPC elements with their pre-mounted windows and doors are ready for assembly, a Type 1 house (see Figure 4-23) can be assembled within one working day. This fast assembly also contributes to the possibility of building many Type 1 houses in the course of a year and at the same time it prevents theft or unauthorised occupation, as the houses are closed in the evenings
- The local building materials (about 99%) can be used without any quality problems. The only exception to the use of local material is a special concrete binder that is sent from Denmark. In result, the use of local material creates domestic jobs and reduces CO2 emission that otherwise would have been caused by transportation from abroad
- The scalability of the low-cost family is high. This means that when, for example, the production has to be doubled or halved it can be done relatively fast at low cost
- The price of a 40m<sup>2</sup> stand-alone house (basic model) based on the low-cost product family does not exceed 55.706 ZAR. This means that the case company can continue building the low-cost houses without generating losses and the housing programme can accordingly achieve its yearly targets.

### ***Modularity***

Modularity has been achieved in several facets. For the customers this means that they can upgrade their houses with extra rooms, a veranda or a bigger kitchen at a low price at the time of ordering. Upgrading is possible in all situations where the housing programme facilitates a contribution of the end user. Besides, modularity can also be achieved by using additional means; e.g. by giving the customer or resident the possibility to enhance the house by adding a rainwater collector that gathers rain water from the roof facilitating cultivating a garden for the house. Another benefit of achieving modularity is that it also is possible to improve the houses with solar panels for generating power for hot water, lighting, charging computers, cell phones, and other consumption. Also, here the housing programme has to allow this kind of improvement.

### ***Knowledge transferred back to the high-end product family***

- The high degree of standardisation contributes to a high throughput in production. The high-end product family needs to be examined for possibilities to increase standardisation and to get away from the current high level of uneconomic flexibility
- The use of prototype elements, drawings, and verbal explanations instead of lengthy documents has been very successful. This method of controlling the scope for a product family could also be introduced to the other product families, which, however, would mean to go away from a systems engineering best practice approach. It has to be examined to what degree this could be done while still maintaining sufficient documentation and living up to described processes
- The rather effective way of teaching new local staff and the team, created a very inspiring feeling during the teaching sessions and should further be applied to staff working on the other families as well. Flying the key personnel of the case project to South Africa in order

to participate in building low-cost houses could be one way of transferring the new knowledge and a positive team spirit back to Denmark

- This new knowledge gained by developing and implementing a product platform for low-cost housing will contribute to improved efficiency and reduced prices in the high-end family, as many decisions that had been taken on the high-end product family have been seriously challenged. An example is the very high focus on the factor cost for the low-cost family that has never been enforced to such a degree on the high-end product family.

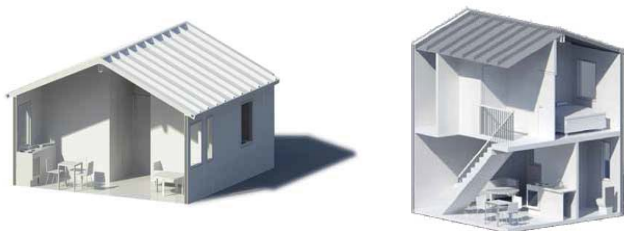
Having summarised the main observations, in the next section the results of implementing a low-cost product family into the case project are discussed.

### ***High level results of making a low-cost product family***

As anticipated, from a technical and process point of view, it was indeed possible to develop the low-cost product family and build houses based on it within the estimated time. Due to the active use of requirements management, the scope of the new product family was clearly defined, while market segment-wise there was no overlapping with the existing product families. From a societal point of view, building low-cost houses at high speed helps ensuring that more people have decent housing and thereby producing an increase in quality of life. Furthermore, a relatively fast, cheap and secure assembly, contributes to reducing the large backlog in the low cost housing area. Thus, as demonstrated by the case company, local job opportunities together with relevant education and training are created. This increases the standard of living and improves future chances for personal development. Houses made from HPC are solid and have according to Danish Standard (2001) a minimum life expectancy of 50 years, while in practice concrete companies often calculate with 70 or more years. This is much higher than what most housing objects currently have. This longer life expectancy makes it possible for a house owner to take a loan out on their house, which in turn can contribute to starting up financial businesses and thereby to strengthening the domestic economy.

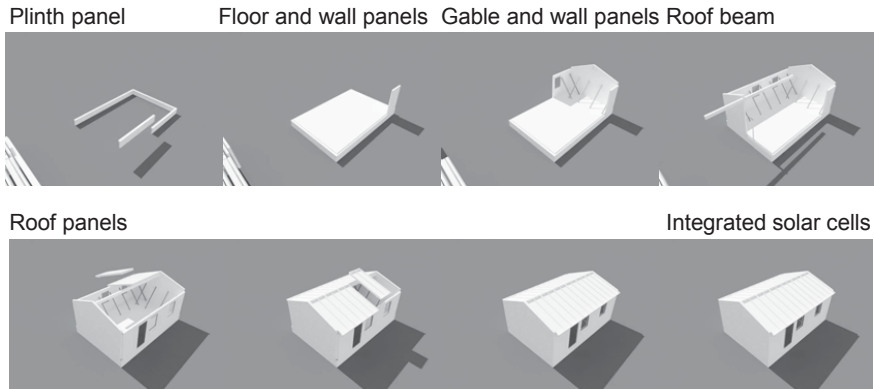
### ***The low-cost product family and the use of modularity***

The low-cost product family currently supports three types of houses, of which two will be explained further in this paper. All houses based on this platform can only be ordered in a light or in a dark version. Each of them comes with two different surface structures, a smooth and a brick-like one. Altogether the customer is offered a limited number of choices, as all concrete elements, windows, doors, materials, sizes, and interfaces are completely standardised. This radical standardisation is the main difference from the high-end product family, for which more variety and a higher degree of customisation is available. Figures 4 (Type 1) and 5 (Type 2) show two types of 40m<sup>2</sup> houses, that are based on this new low-cost product family.



**Figure 4-22: Two different 40 m<sup>2</sup> buildings made from HPC – Type 1 and Type 2**

Modularity on the low-cost product family exists on two levels. On the element level, the HPC elements are prefabricated and scaled to approximately 1,2m in width. Figure 4-23 illustrates the conceptual assembly of a Type 1 house based on those elements. On the building level, several variants of the Type 1 and Type 2 house exist. The Type 1 house can be produced as basic 40 m<sup>2</sup> model or as one of four variants, where modules like a veranda or extra rooms can be added. Depending on what modules are added, the size of a Type 1 building can go up to 56 m<sup>2</sup>, as depicted in Figure 4-24.



**Figure 4-23: A Type 1 house assembled from prefabricated HPC elements**



**Figure 4-24: The five variants of the Type 1 house**

#### ***Knowledge transferred back to the high-end family***

A lot of knowledge has been gained when making the low-cost product family. Some of the key learning points were:

- Even though there were only a few choices the customers could make, when ordering a house, the offered variety appeared to be suitable for this market segment. This will result in a review of the high-end product family, to ensure that customers are not offered an infinite degree of variety and that the financial contribution per variant is high enough. Non-profitable variants should be removed from the platform

- Starting the low-cost product family from scratch, rather than trying to take the high-end product family as a starting point for scraping off layers, turned out to be the right decision. In hindsight, it is the belief of the author, that it would not have been possible within the given timeframe to achieve the cost goal per unit using this approach
- This was the third product family the case company developed. Since the high-end and insulation panel product families were well defined and linked to the company strategy, developing a third product family took considerably less time. The experienced staff and the right software tool support, such as the use of product CSs, contributed strongly to the fast development of this platform

#### 4.4.3.3 Conclusion

In this article it has been described how a low-cost product family has successfully been developed and implemented in the low-cost housing segment within the construction industry. The houses based on this platform are built up in a modular approach, where modularity has been achieved both on element and on building level, resulting in buildings which can be delivered in several types and variants. The main difference compared to a coexisting high-end product family is the high degree of standardisation and the limited number of commercial variants, which has been adapted according to the requirements of this market segment. Besides, the application of requirements management as described by INCOSE has resulted in working descriptions containing much less text, but with more pictures and drawings instead (Stevens and Martin, 1995). This positive attempt to use product families in the low-cost segment of the construction industry confirmed the main proposition of this research and shows that the product platform approach is a valid strategy for meeting the low cost housing demand of developing countries.

Despite the promising results, further research is needed in the following vicinities: Since there is a high need for decent housing, smart solutions have to be found for quickly producing a high amount of houses, which are cheap and long lasting. If companies find a way of addressing this issue in a profitable manner, they are more likely to participate in this enormous task. At the same time it is important that the applied housing solutions are sustainable, as according to EU, 2010, residential and commercial buildings are responsible for about 40% of the total energy consumption and 36% of the total CO<sub>2</sub> emission in the European Union. Other parts of the world will soon face similar situations to those described above, if there is no sufficient focus on sustainability when producing such a vast amount of buildings. To this end, further research is needed in how product platforms, by means of effective development and production, can further contribute to the low-cost housing segment and to the construction industry in general. Finally, it is necessary to further optimise the economy of sustainable low-cost housing based on life cycle considerations. Once this has been done, it has to be examined how the gained experience can support in maximising the high-end segment in countries like Denmark.

#### 4.4.4 Paper I: Method detailing

<b>Title:</b>	<b>Extending product modelling methods for integrated product development.</b>
Published in:	Proceedings of the 19th International Conference on Engineering Design (ICED13): Design For Harmonies. Vol. 4 Design Society, 2013. p. 219-228
Case studies:	#6

##### 4.4.4.1 Research objective and research question

Based on the developed understanding for architecture modelling, this study aims at exploring the possibility of integrating customer requirements directly into architecture models through fuzzy logic. Fuzzy methods quantify the strength of with estimated values, which help to evaluate an impact of a change in requirement. A case study is being permed to test an initial model. The gained results accommodate answering *RQ3.1*.

##### 4.4.4.2 Research Contribution

###### ***Product requirements development model***

When assessing the development task of a physical product from a redesign perspective, separately considered, each of architecture modelling methods reveals a limitations in providing the essential overview and insight of requirements coming from different stakeholders and their effect on the product architecture. Supportive methods should be able to describe how the customers' requirements are realized, what engineering solutions have to be used, what is the physical structure of the products, and how are these produced. Since it is in particular important to make visual not only which, but also how parts are related, connected or assembled, hierarchical relationships and attributes have to be considered as well. Consequently, the presented Product Requirements Development (PRD) model builds on the existing capabilities of the PVM technique in mapping the stakeholder's needs to design solutions. Based on an industrial case, the method addresses both, (1) how complex hierarchical relationships can be mapped and (2) how in turn a resulting product design may affect the stakeholders.

A major difference between the product specification process in mass customization and the development of a new product in a product family is that the first one should fulfil the specific need of a single customer based on available solutions. The latter case needs to consider several stakeholders simultaneously, the impact of new requirements on the product architecture and the effort needed to realize the solutions are unknown. Here, the requirements from each stakeholder have to be evaluated in depth, as they need to be challenged, transformed, and tested by the designers. Since updated requirements have to be set in relation to the current product portfolio, it is eventually inevitable to have suitable models showing the existing product architecture in place. As illustrated in Figure 4-25, following the notation of the PVM technique, first, if not already available, a generic model of the product family at hand is created. With an additional "Process View", life cycle considerations related to production, transportation and assembly can be included.

Next, similar to the QFD method, in a second step current stakeholder requirements are identified and directly modelled within the existing hierarchical product architecture of the PVM. As indicated in Figure 4-25, such requirements can appear in the different perspectives (views) of the model. The most common ones are typically driven by the market and are to be placed within the Customer View of the model. Technology driven requirements on the other hand are mapped in the Engineering View. Besides, requirements coming from other domains can potentially be mapped in the corresponding views. On the left side of the PVM, in the Stakeholder Evaluation Matrixes (SEMs), the requirements are graded and prioritized across the views according to their importance from 1 (low) to 5 (high).

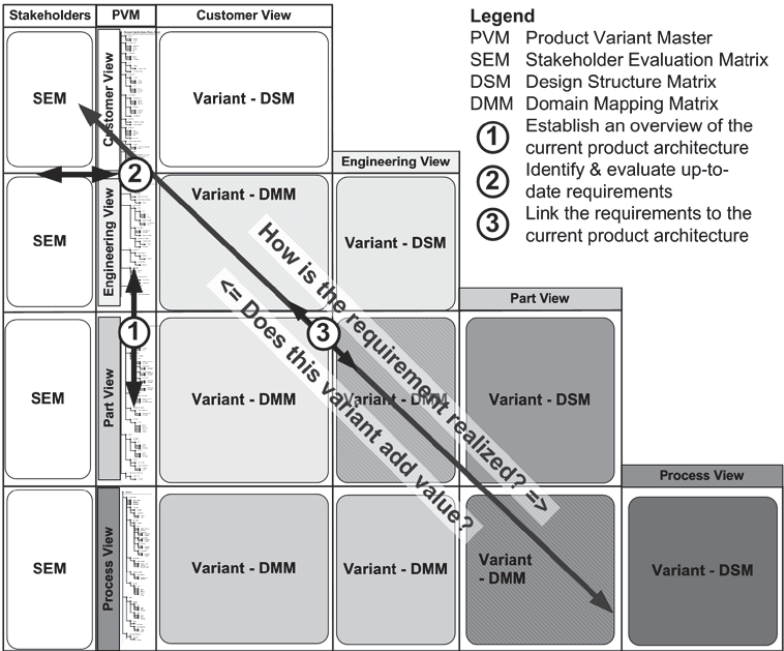


Figure 4-25: Product requirements development model

The right-hand side of the PVM displays both, the downstream and upstream impact relationships. Complementary to the DSM and DMM technique, the effect of the requirements on other customer attributes, engineering solutions, physical parts, and processes can be mapped through inter-domain (Variant DSM) and intra-domain matrixes (Variant DMM). The difference to the well-known DSM technique hereby is that each side of the matrix is linked to the PVM structure, and therefore allows a concise expression of hierarchies and relationships, e.g. part-of or kind-of structures and attributes. Alternatively, to link hierarchies, variants and attributes with each other using standard matrix-based modelling methods, for each of the seen "Variant DSMs" or "Variant DMMs" a huge number of DSMs or DMMs is needed. Thus in order to obtain the overview of the resulting changes, at this point integrating the PVM technique with the DSM method appears to be beneficial. Having described the principal makeup of the PDM model, in the following paragraph the model will exemplarily be applied on the case study.

In the case example first (Step 1) a PVM model of high performance concrete sandwich elements has been created. Figure 4-26 illustrates a small segment of the entire model, where in Step 2 upcoming requirements were modelled directly into the established PVM. Market driven requirements were illustrated in "green" in the Customer View of the PVM. Here they e.g. concern a new surface and colour for the concrete panels, as well as a different heating solution. Besides the requirements from the market, in technological development projects, requirements could also be triggered by the used technical solution as indicated by the "red words" on the engineering level (Engineering View). With the use of the different colours, change requests in the model could quickly be retrieved. Next, on the left-hand side of the PVM the stakeholders of the project were mapped into the described SEMs. In order to formally prioritize their preferences for all new requirements, their individual assessment was aggregated to the sum at the right-hand side of each SEM. Since in the case study all stakeholders had the same relative importance, no other proportional weighting for prioritizing the requirements was needed. It should be noted that in other cases different pri-



oritizing strategies may exist. In some projects stakeholders may either have a greater voting right than others or other rather strategic aspects might be more important. Either way, at the end of this step arising requirements should be given a relative priority.

### Applying the suggested model

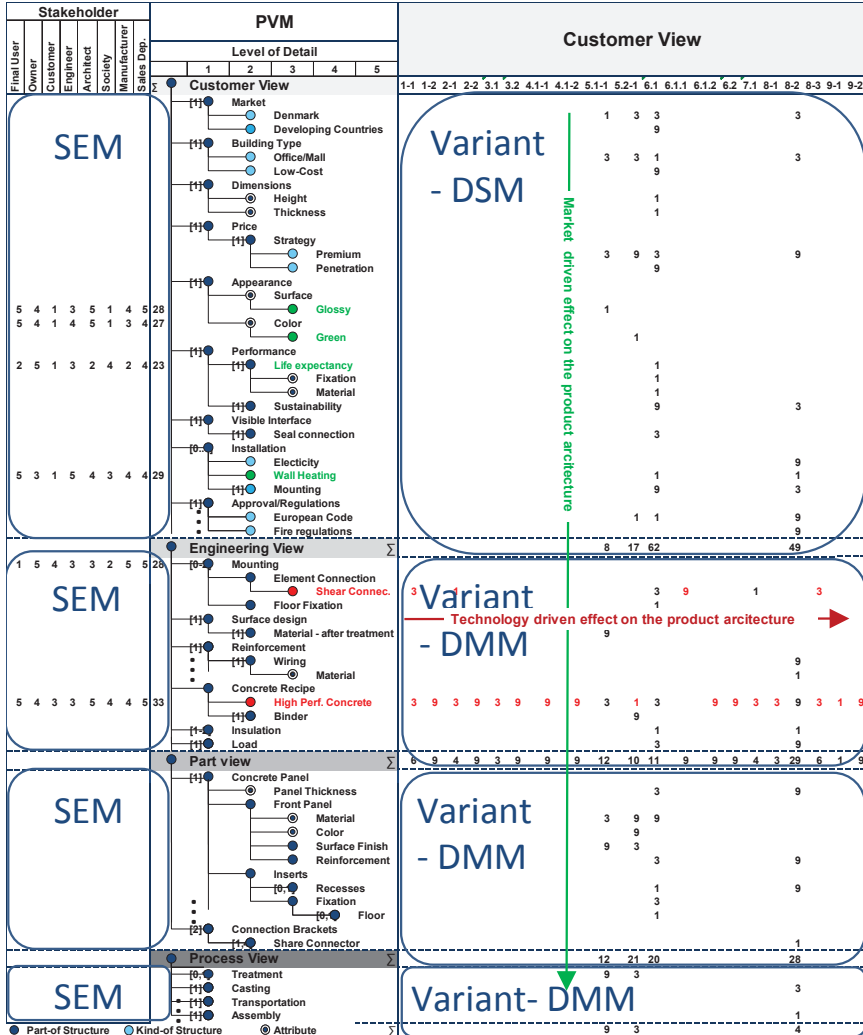


Figure 4-26: Requirements evaluation

In Step 3, as illustrated on the right-hand side of the PVM, the impact of the requirements was modelled according to the fuzzy logic model. By grading the strength of the relationships with numbers (1, 3, and 9) (Ko, 2010), again it was possible to formalize how strong the effect of each requirement is on the current product architecture. Rather than only showing if there is a relationship at all, a higher number indicated a stronger effect. Equivalent to the active and passive sum of a matrix (Lindemann et al., 2009), for each Variant DSM or DMM, the total impact of each requirement was calculated at the bottom as the sum of the individual relationships. However, in order to obtain the overview, Figure 4-26 shows

only partly the downstream effects of the requirements. For example, the impact on the stakeholders from the new “High Performance Concrete” (HPC) is depicted through the PVM structure of model. It has both a relatively high priority in the SEM and strongly affects the entire product architecture. “Life expectancy” on the other hand has been less prioritized by the stakeholders. Even though it has a significant effect in the Variant DSM in the Customer View, downstream traces (shown through the Variant DMMs) are less impaired. Another example shows how even more detailed requirements, such as the new “shear connection” can directly be shown within the model. Since “shear connection” is a part-of the mounting group, its indirect effect on a higher level of detail can be seen. In relation to the other requirements, it had a moderate priority from the stakeholders. But since it is not directly visible to the end users and affects a rather limited number of physical components, its impact on the remaining architecture is narrowed. All in all, by integrating the different modelling methods, this method shows how requirements have been graded by the stakeholders (upstream effects) and how they in turn affect the product architecture (downstream effects).

#### 4.4.4.3 Conclusion

Product models, capable of representing how updated customer requirements affect the product lifecycle, enable designers to preserve the overview of the current product architecture, to better coordinate upcoming development activities, and moreover to plan and to calculate alternative solutions. By making use of established product modelling methods, such as the UML-based PVM, this paper contributes to an integrated PD process, which aims at better responding to the requirements of modern product development. Through the integration of several modelling techniques, the presented PRD model overcomes some of their individual drawbacks, e.g. the representation of hierarchical levels, product variants and attributes, while still being able to visualize correlations. Therefore, with the right integration, the PRD model expands the individual modelling possibilities. In sum, it (1) enables the representation of complex hierarchical relationships in a generic product model, (2) links and evaluates updated requirements to several levels of the product architecture, and (3) illustrates how these requirements have an upstream (towards stakeholders) and downstream (towards production) effect on the product architecture. However, in order to address all subsequent aspects of the PD process and therewith to explore the full potential of the model, further research needs to be done. It would for instance be interesting to investigate how matrix-based analysis methods, such as partitioning, could be solved with the Variant-DSMs and – DMMs of the model. Here, future research could for instance focus on what impact structural improvement of the product, through e.g. modularization, could have on the entire product architecture as well as on new requirements.

#### 4.4.5 Paper J: Development and investigation of methods and tools for formal of architecture synthesis

**Title:** **Supporting the design and mass customization of product family architectures using computational structural analysis methods**

Published in: in journal review

Case studies: #10

##### 4.4.5.1 Research objective and research question

Based on the developed understanding for architecture synthesis, this study reflects on the architecture modelling requirements from Section 3.1.3 and proposes a method which aims at better addressing the discussed needs. Furthermore, the method is tested on a practical case to enhance the understanding for answering *RQ3.1*, *RQ3.3*, *RQ3.4* and *RQ3.5*.

##### 4.4.5.2 Research contribution

###### ***Reflection on architecture synthesis***

As initially elaborated in Section 3.1.1, platforms and modules built into product family architectures have been reported to facilitate working with diverse product variants (AlGeddawy and ElMaraghy, 2013). In this context, architectures have been described as an abstract structural representation of the functional units and the corresponding physical components of engineering artefacts (Ulrich, 1995). Their development is complex and long lasting and their performance can have wide-ranging effects on the success of manufacturers (Yassine and Wissmann, 2007). The design of architectures suitable for customization raises additional difficulties to organizations, since the right product composition and part compatibility needs to be ensured. Product CSs have been developed by software vendors to handle this demanding requirements for information processing, storage and retrieval of feasible variant combinations (Trentin et al., 2011). CSs or configurators are software-based expert systems that capture the generic architecture of product families in a computer model, through which users are supported in creating feasible product solutions with a minimum number of choices (Hvam et al., 2011). Combined with well-designed product family architectures, companies utilize product configurators to mass customize their offerings, i.e. to automate operational activities related to product customization and to increase their efficiency to a level which is close to mass production (Jiao et al., 1998).

However, it can be difficult to identify good product family architectures during product design and to sustain their subsequent implementation in a CS, since they are qualitative and supporting methods during development and verification are limited (Li, Xie, et al., 2011). At the same time, configuration software vendors are of no help in this respect, as they are typically not interested in providing a transparent and easy way to create and communicate product family architectures, but rather emphasize consulting services around the modelling and maintenance of product families (Forza and Salvador, 2008). Hence, with the development progress of product families, software experts have problems in keeping an overview of what had been implemented in the computer model and verifying the obtained architectures with domain experts, making it one of the main reasons why designing and mass customizing products is still difficult to achieve (Haug et al., 2012).

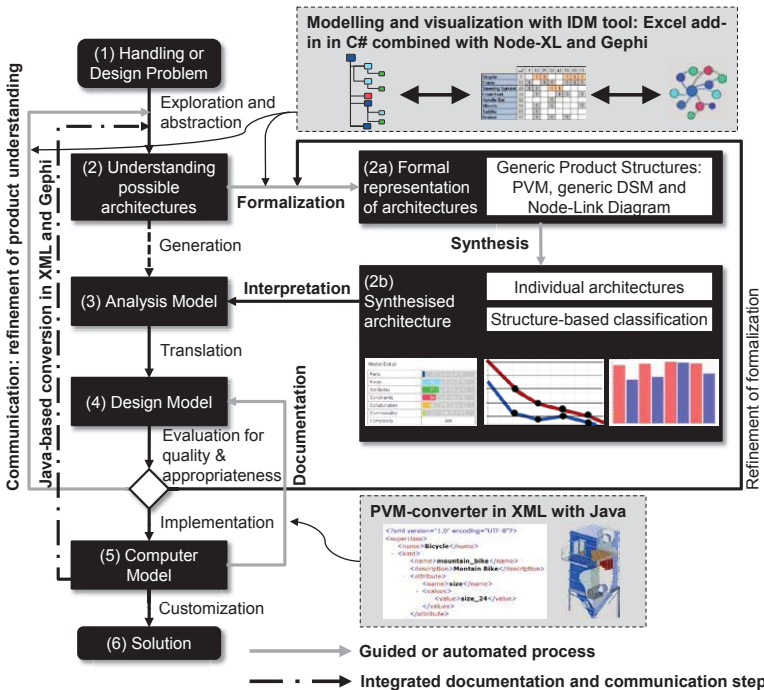
To address this issue, this paper proposes a computer-assisted approach which allows domain experts to document, communicate and design entire product family architectures build into CSs more effectively. The approach is complemented with a case study of a major plant and machinery provider of highly customizable products to develop a concrete method on a real world problem. The method combines the capabilities of a state-of-the-art configuration software with automatically generated grammar graphs representing the implemented architectures. The graphs are modelled with an integrated design model (IDM),

using the suggested extended modelling techniques for generic structures. The IDM tool is further employed to assist domain experts in synthesising feasible architectures and to computationally evaluate their structural characteristics through a series of metrics, potentially leading to better solutions. The obtained results indicate that the method has value for industrial praxis.

To validate it's applicability of a real case, the method has been further tested in an empirical architecture design problem.

**Applying a proposed formal synthesis method**

To demonstrate a proposed approach, a case study was conducted on an industrial product architecture design and customization process at a major provider of plant and machinery applications. The collaboration with the company was established throughout 2013 the beginning of 2014 and involved several semi-structured interviews lasting between 1 and 2 hours as well as half-day workshops with a team of domain experts, two engineers and one IT expert. The domain experts are part of a larger physically disconnected team, which is responsible for the coordination of the architecture design and its implementation in a CS. In addition, full access was given to architecture models of selected product families and their development over a period of 12 months. The objectives for the study were (1) to identify the major concerns for the architecture design and implementation process and (2) to address them with a new approach for generating architectures through the formal synthesis method proposed in Section 3.1.3.



**Figure 4-27: Proposed method to support product family architecture design and customization**

**Consequences of the informal approach at the case company**

At the beginning of the case study, the company had employed an informal approach as described in Section 3.1.2.2. In response to an increased market demand for a rapid and robust

customization, the company has been implementing a growing part of their product line into the commercial CS Tacton (Tacton Systems, 2014). By the end of 2013, more than 30 different product families of highly customizable industrial applications, e.g. conveyors, pumps and valves, have been used by product managers and technical salesmen internally to support customers in specifying their own product requirements. Comparable to other modern configurators, the software provides an object-oriented development environment as described in Section 3.3.2 for the design of generic architectures. To facilitate the understanding of the architecture, the computer models may be complemented with comments and technical or illustrative pictures.

A representative product family architecture consists of several thousand interconnected elements and may include components that are produced internally or sourced externally by sub-suppliers. The architecture design is generally organized as an incremental process with regular iterative steps and requires the latest architecture to be used as a starting point for the new solution. The objective of the design work typically involves considerations for how increase the reuse of common parts, while maintaining the necessary product variety or simply for how to comply with changing legal requirements. The lack of a formal and/or integrated computer support forces the organization to use a considerable amount of resources for designing and coordinating developed architectures. Since the computer models per se can neither be extracted nor visually displayed, design initiatives have to be compared manually against the implemented architectures within the configurator. Moreover, both product managers and engineers find it difficult to verify if a committed design objective, e.g. to increase modularity of certain sub-assemblies, has actually been obtained. Even if substantial rework may be done to achieve this goal, the informal approach provides no method to demonstrate any positive evidence pointing towards the obtained result. In consequence, the insufficient control mechanism of the informal approach increases the risks for delayed product launches and inconsistent architectures.

### ***Applying a proposed documentation and visualization strategy***

Being aware of this challenging situation, engineers and configuration software experts are pressured from several directions. They have to improve their productivity when designing and implementing architectures and to provide more transparent planning reports to the product management about their progress. This may be achieved by the proposed method illustrated in Figure 4-27. The described method proposes a pragmatic solution, which allowed to be implemented and tested within the limited time the study. Comparable to many other computer systems, the employed configurator allows by default to save the computer files in the Extensible Markup Language (XML). The XML standard is a text-based format which is frequently used to represent machine-readable structured information, such as documents, configuration status and invoices. Due to its simple and well organized structure, it has been widely-used to share context specific data between programs and people, potentially enabling small models to be understood without any additional software support (XML Working Group, 2010). These XML files created by the configurator contain the encrypted product family architecture of the computer model along with other program specific information. This suggests that the computer models created in Tacton can with relatively little development effort be decoded or converted in a legible modelling format using XML.

However, as no XML standard per se is capable of representing generic architectures, a format was created which resembles the discussed PVM notation in Section 3.3.2. This was done using a self-developed Java-based application, a parser called 'PVM converter'. The application utilizes simple data mining techniques to decode the relevant information within the configurator files and to restructures them into the PVM format. An example of an XML-based PVM file can be seen in Figure 4-28. The illustrated XML syntax uses the integrated identifiers from the XML language to express part-of-structures, kind-of-structures, attributes and constraints. Apart from documenting the architecture of the computer

model alone, the application complements the architecture with comments and path references to pictures which have been included within the knowledge base of the CS.

```
<?xml version="1.0" encoding="UTF-8"?>
<superclass>
  <name>Bicycle</name>
  - <kind>
    <name>mountain_bike</name>
    <description>Montain Bike</description>
    - <attribute>
      <name>size</name>
      <values>
        <value>size_24</value>
      </values>
    </attribute>
  </kind>
  - <constraint>
    <name>Frame.wheel_size = Wheels.size</name>
    <description>Frame.wheel_size, Wheels.size </description>
  </constraint>
  - <part>
    <name>Frame</name>
    <cardinality type="integer">1</cardinality>
    - <kind>
      <name>ibis_carbon</name>
      <description>Ibis, Mojo carbon </description>
    </kind>
  </part>
  + <attribute>
```

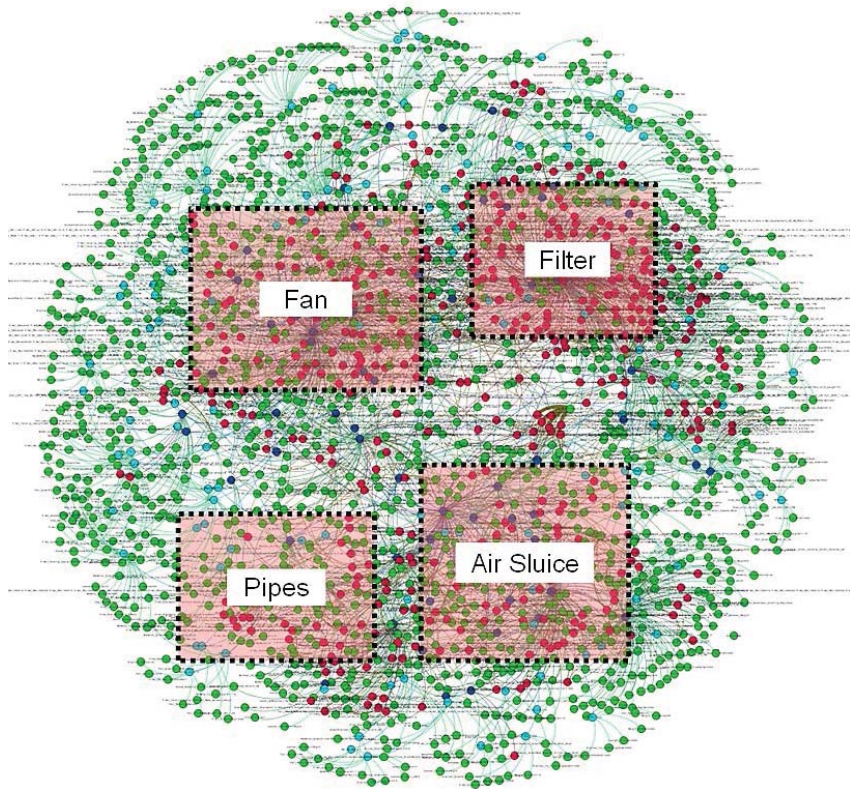
**Figure 4-28: Illustrative XML-based example of a PVM**

To obtain consistent design models and to communicate them effectively to various stakeholders, the created XML-based PVM models need to be expressed graphically with the discussed grammar methods. Since no dedicated software tools hitherto exist for creating the required generic architectures, a modest solution presented in Figure 4-27 is to use of the capabilities of existing open source software and to adjust it to the context specific requirements. This has been realized through an IDM application, a Microsoft Excel add-in which has been developed in C#. The IDM software is used to generate semantically correct PVM and generic DSM models out of the previously created XML-based PVM model. The software has been further combined with the freeware visualization software NodeXL and Gephi, which are two very frequently used tools for studying social networks with node-link graphs (The Gephi Consortium, 2014; The Social Media Research Foundation, 2014). An export function within the IDM software has been developed to ensure the consistency of the generic structure. It converts the XML-file into the discussed convention of node-link diagrams and exports it automatically into the relevant freeware formats, e.g. csv or .gephi. A major advantage of utilising widely accepted standard software is that the obtained solution may be established with relatively low development costs. Furthermore, as no or little changes are made to the existing IT infrastructure in the company, the obtained solution is more likely to be accepted by the stakeholders.

The documentation and communication process may alternatively be combined into one integrated step, so that any user of the CS can directly share and discuss the latest version of a particular architecture which is being run within the configurator. As displayed in Figure 4-27 the process has been realised by integrating a web-based function within the UI of the configurator, which when selected encodes the underlying computer model first into the described XML-based PVM file and subsequently decodes it into a node-link graph in form a svg- or pdf-based Gephi model. For an industrial company offering a variety of custom tailored products the automatic visualization of the entire generic structure proved to be very valuable in praxis. Product managers and technical salesmen using the configurators are typically very experienced with the provided products. Having a method which allows them to instantly communicate the architecture in use graphically through e.g. a web browser significantly increases the transparency of the achieved solution and eventually enables the consideration of a larger amount of product experience into the design process. Furthermore, if used externally, the method facilitates companies to engage their customers in co-creating new product functionalities and thereby to utilize external resources to drive



their innovation processes (Martínez-Torres, 2013). Figure 4-29 displays an example of an automatically created generic architecture of a dedusting system provided by the company. The graph shows a major section of the entire family, which in total consists of roughly 3000 elements. The product is installed in production environments exposed to extreme dust and dirt to keep critical manufacturing areas clean during operation and maintenance. In praxis this is being achieved by creating a negative pressure in the production equipment in order to prevent that generated dust disperses to the surroundings. The major building blocks are illustrated by the shaded areas in the model and include a fan and a filter system, several pipes, as well as an air sluice.



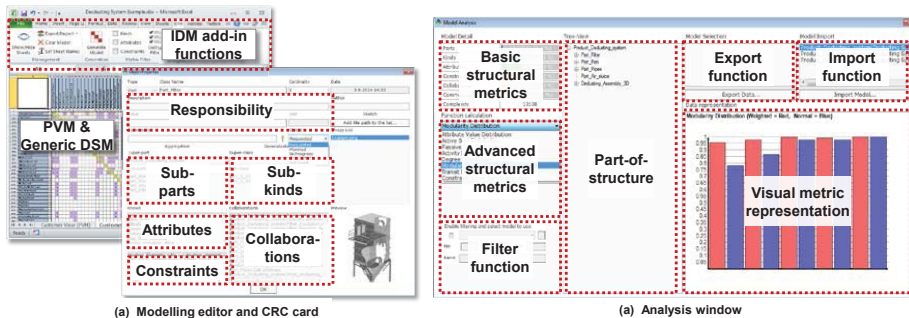
**Figure 4-29: Generic node-link diagram showing the discussed degusting system**

### *Formalizing and synthesizing architectures*

With the described documentation and visual communication of the computer model, the graphs are being used to create an understanding of the design problem and to narrow the development effort to the relevant aspects. The design process may be supported by the IDM software. Part (a) in Figure 4-30 shows the modelling environment of the IDM tool, where equivalent to the guided know-ledge base editor of modern configurators (Liao, 2005), the user is assisted in creating valid architectures inter alia by following the in Section 3.4 discussed generic syntax. Data mining techniques have been further implemented in the software to guide the user in formulating feasible constraints and to consider the discussed aspects of encapsulation.



To abstract the model towards the particular design problem, domain experts may choose to collapse or filter out unessential elements. CRC cards are automatically generated and include the implemented pictures and comments of the computer model. To add additional elements, the desired parent class is selected and element details are added in an automatically generated CRC card. Besides, the cards are used to describe additional information about the implementation status of the model (e.g. in progress or implemented) and the responsible domain expert for the particular object. In large design projects this particular feature can be very useful, as it helps project experts in keeping track of the development work and managing the responsibilities of tasks. Depending on the user's preferences, the architecture can be designed within both, the PVM or the generic DSM notation, where furthermore the user can switch dynamically between the IR/FAD and IC/FBD convention of the matrix (see Sect. 3.2.1). Eventually, to synthesize feasible architectures within a wider physically disconnected team of domain experts, each architecture may be communicated using the generic models in any of the three grammar graph techniques.



**Figure 4-30: IDM software tool showing a collapsed generic DSM model and a CRC card (a) and the analysis window (b) on the example design problem**

### *Interpretation and refinement of synthesized architectures*

The majority of these features originate from studies for social network analysis (Bounova and de Weck, 2012). The recent increase of accessible data from social network applications has amplified the number of such studies (Boyd and Ellison, 2007). Because a large number of data sets has to be handled, this growing research area quickly resulted in better computational solutions, which display and automatically analyse the structural properties of a network (Butts, 2008). The applied analysis algorithms and representation forms are based on a common theoretical foundation of graph theory (Barnes and Harary, 1983), which allows to characterise and reliably compare networks using a common language. Moreover, researchers can base their analysis on proven mathematical notations, which creates additional transparency of the achieved results (Boyd and Ellison, 2007). Several studies in product architecture design have adapted aspects from graph theory. Since architectures modelled as a connection of elements per se imply little or no information about any particular condition of quality, it is necessary to consider quality indirectly through the presence of additional features. The contributions most relevant to this research deal with structural properties of elements in single products at the individual and group levels.

To support domain experts in comparing architectures of different products or selecting between alternative ones of the same product, each model may be evaluated quantitatively using a set of metrics. A metric can appraise a specific aspect of an architecture in order to evaluate a quality which corresponds to any lifecycle objective of the product (Huang, 1996). Measures addressing product architectures typically include aspects of variant-oriented design (see Sect. 3.1.1), e.g. product complexity (Sinha and de Weck, 2013), modularity (Sosa et al., 2007), or communality (Thomas, 1992), and may in combination or alone access the considered design problem. However, since the majority of metrics proposed in

literature are based on graph-theoretical characteristics of social networks (Bounova and de Weck, 2012), they need to be adjusted to the convention of generic structures for product families. Eleven of them are described in Table 4-11 and refer to their impact on the design work of the entire architecture of a family or to a chosen sub-section A. Metrics 1 to 4 in the table show basic characteristics of the architecture (direct structural properties), e.g. the number of parts and variants in a model, while metrics 5 to 11 indicate the related indirect structural properties. The measures may be used by domain experts to explore the synthesized results towards a preferred solution.

The information gained from the metrics can be presented visually with commonly used chart formats, e.g. bar charts, and may help to explore structural patterns or ‘interesting’ architecture areas. This may be supported either by listing the values unsorted within the charts in the sequence of the index numbers in the model (see Sect. 3.2.1), or by showing them with an ascending or descending order against an absolute scale, e.g. time. This method is realised within a developed analysis tool for the IDM add-in. Part (b) in Figure 4-30 displays a screenshot of method applied on an example problem of the dedusting system, where the weighted and normal modularity of the major building blocks have been graphically displayed. The proposed interpretation technique was used by the domain experts on a variety of design problems, where for example the (structural) complexity of architectures could be reduced explicitly. This was achieved by abstracting the design problem to building blocks with higher potential for modularity improvements. The suggested design alternatives could then be evaluated iteratively with regard to their structural impact on the overall architecture, potentially leading to higher overall design quality.

**Table 4-11: Structural metrics for a formal product family architecture synthesis**

Metric	Formula	Description	Normalized by
1 Parts	$n_p(A) = \sum_{i=1}^n p_i$	More parts require more design work (Hodbay, 1998): the sum of all parts $p_i$ in architecture (section) A containing $n$ elements	$n$
2 Kinds	$n_k(A) = \sum_{i=0}^n k_i$	Higher variety requires more design work (Martin et al. 2002): the sum of all kinds $k_i$ in architecture (section) A containing $n$ elements	$n$
3 Attributes	$n_a^{(u)}(A) = \sum_{i=1}^{n_p} \left( \sum_{j=0}^{n_g} a^{(g)}_{ij} + \sum_{t=0}^{n_v} a^{(v)}_{it} \right)$ $a^{(u)}_i$	More functionality requires more design work (Sinha et al., 2013): the sum of all unique attributes $a^{(u)}_i$ in architecture (section) A containing $n_p$ parts, with all generic attributes $a^{(g)}_{ij}$ and all variant attributes $a^{(v)}_{it}$	$n$
4 Collaborations	$Col(A) = \sum_{i=1}^{n_p} c_i$	More interfaces require more design work (Sosa et al. 2007): the sum of all collaborations $c_i$ in architecture (section) A containing $n_p$ parts	Maximum possible degree $Col(A)_{max} = n_p * (n_p - 1)$
5 Commuality	$Com(A) = \frac{\sum_{i=1}^{n_p} \left( \sum_{j=0}^{n_g} a^{(g)}_{ij} \right)}{\sum_{i=1}^{n_p} \left( p_i \sum_{j=0}^{n_g} a^{(g)}_{ij} \right) + \sum_{i=0}^{n_k} \left( k_i \sum_{j=0}^{n_v} a^{(v)}_{ij} \right)}$	Higher commonality requires less design work (Jiao et al., 2000): the ratio between all common objects and their properties $a_i$ (all parts times their generic attributes) compared to all objects and their properties (all common objects plus all kinds times their variant attributes) in architecture (section) A	Maximum possible degree $Com(A)_{max}$ for $n_p=0$ or $n_v=0$
6 Complexity	$C(A) = n_p(A) + n_k(A) + Col(A)$	Higher (structural) complexity requires more design work and communication effort (Prasad, 1998); it is based on number of components, their variety and interdependence (Gerald et al., 2011): the sum of all parts, kinds and collaborations in architecture (section) A	-
7 Active sum	$As(A) = \sum_{i=0}^n l^{(a)}_i$	Parts with high active sum are more significant in design (Lindemann et al., 2009): the sum of all interfaces $l(a)$ that emerge from a part	-
8 Passive sum	$Ps(A) = \sum_{i=0}^n l^{(p)}_i$	Parts with high passive sum are more influenced in design (Lindemann et al., 2009): the sum of all interfaces $l(p)$ that affect a part	-
9 N-modularity	$N_m(A) = \frac{\sum_{i=1}^{n_m} l^{(m)}_i}{\sum_{j=1}^{n_o} l^{(o)}_j}$	Higher modularity facilitates variety and concurrent design and maintenance; modules are tightly connected components inside a cluster and loosely connected to others (Sosa et al., 2007): the normal ratio $N_m(A)$ between all interfaces $l(m)$ within a selected section $n(m)$ compared to its interfaces to other parts $l(o)$ in architecture (section) A containing $n(o)$ parts	-
10 W-modularity	$W_m(A) = \frac{\sum_{i=1}^{n_m} w^{(m)}_i}{\sum_{j=1}^{n_o} w^{(o)}_j}$	Modularity may be weighted, to account for multiple connections between two components (Gershenson et al., 2004): the weighted ratio $W_m(A)$ between all interfaces $w(m)$ within a selected section $n(m)$ compared to its interfaces $w(o)$ to other parts $w(o)$ in architecture (section) A containing $n(o)$ parts	-
11 Constraint active sum	$Cas(A) = \sum_{i=0}^n l^{(c)}_i$	Constraints with high active sum are more significant in design (after Lindemann et al., 2009): the sum of all constraint links that emerge from a constraint $l(c)$	-

#### 4.4.5.3 Conclusions


MC provides a promising concept to respond rapidly to individual customer needs. It requires from manufacturers to effectively design, implement and maintain suitable product family architectures in CSs, which are then used to efficiently support the customization process. This paper has investigated the application of related modelling methods and formal computer-based approaches to facilitate this process. In particular, the paper argues that architectures can be presented explicitly through appropriate grammar graphs which consider common generic modelling standards if the UML language. This systematic documentation and visualization of architectures allows the integration of a widespread internal product expertise as well as stronger customer engagement. Moreover, the quality of architectures may be evaluated objectively through computational structural analysis methods, making any assumptions about the obtained solution transparent and thereby accessible. The usability of the methods has been demonstrated on an industrial case study of a major plant and machinery provider. The capabilities of a state-of-the-art configurator have been complemented with automatically generated grammar graphs. Besides, the architecture design process was assisted through a computer-based modelling and analysis method consisting of guidelines and visually represented structural metrics.


While the proposed formal computational approach has led to a number of benefits for the case company, the applied methods have been specifically designed to fit the particular needs of the studied industrial praxis. Future research might consider addressing these limitations and thereby extending the relevance of the presented methods. Specifically, the discussed documentation techniques may be applied to a variety of commercial CSs. In addition, a dedicated modelling and analysis system may be developed to obtain a more stable and scalable software solution.

#### 4.4.6 Section summary

This Section 4.4 presented a comprehensive investigation of aspects relevant for answering the third research question (RQ3: How should architectures for mass customizing ETO products be designed and managed?). *Paper F* introduced in Section 4.4.1 employed a survey with manufacturing companies using CSs in support of their specification process. It was learned that predominantly ETO companies with complex architectures used a systematic strategy to architecture design, as discussed in Section 3.1.1. In doing so, the companies reported several benefits, such as reduced product variety and improved documentation and communication of architecture knowledge. *Paper G* presented in Section 4.4.2 revised the created understanding for robust design and proposed ways to enhance this capability through the use of platforms. Postponement was further conceptualized as a two-dimensional strategy for the engineering, production and logistics domain of the customization value-chain, where different feasible strategies were discussed and put into perspective to potential cost-benefit gains. This investigation helped answering *RQ2.1*. *Paper H* and *I* introduced in Section 4.4.3 and Section 4.4.4 refined the understanding of architecture design. The former paper dealt with strategic learning points from different platform strategies across product families. The latter explored detailed fuzzy logic methods to quantify requirements directly into architectures. The outcome of the papers determined the direction for *Paper J* introduced in Section 4.4.5. The study reflected upon the state-of-the art understanding of a consistent architecture design process and a formal synthesis and presented a method based on formal computational structural assessment. The method was used to formally describe preferred architectures for MC in an explicit and visible way, using the in 3.4 developed methods. A case study was used to test the developed model on a practical case. Due to the high demand for data transfer, consolidation and interpretation, several tools were developed to overcome the current limitations of CSs. The so called IDM tool was presented and its functionality with respect to visual analytics was discussed. Finally, strategies for managing the architecture complexity were formulated.

Thereby this section answered a major part of the third research question, as indicated below. However, even though *RQ3.5* (RQ3.5: How can the complexity of ETO architectures in MC be assessed and managed?) was addressed to a great extent on a modelling level, to provide a more detailed investigation of monetary quantifying the changes in architecture, this research question will be further elaborated in the next section.

**RQ3.1:** How can architectures used for mass customizing ETO products be described explicitly and visibly? 

**RQ3.2:** What is suitable architecture design strategy for mass customizing ETO products? 

**RQ3.3:** How can a consistent architecture design process for MC be organized? 

**RQ3.4:** What are preferred architectures for MC and how can they be formally described? 

## 4.5 Improvement of system design and management

This section addresses the last sub question *RQ3.5* (RQ3.5:How can the complexity of ETO architectures in MC be assessed and managed?) through a detailed investigation on architecture complexity strategies for a production systems challenged with growing product variety.

### 4.5.1 Paper K: Detailed investigation of architecture complexity management

**Title:** **Managing complexity of product mix and production flow in configure-to-order production systems**

**Published in:** Proceedings of 21st EurOMA Conference: Operations Management in an Innovation Economy. European Operations Management Association, 2014

**Case studies:** #9

#### 4.5.1.1 Research objective and research question

In designing configure-to-order production systems for a growing product variety, companies are challenged with an increased complexity for obtaining high productivity levels and cost-effectiveness. In academia several optimization methods and conceptual frameworks for substituting components, or increasing lot sizes and storage capacity have been proposed. This study presents a practical framework for quantifying the impact of a two-way substitution at different production stages and its impact on storage and machinery utilization. In a case study the relation between substitution, lot sizing and capacity utilization is quantified, while maintaining the production capacity as well as the external product variety. The results provide detailed insight for the effect of complexity management relevant for answering *RQ5*.

#### 4.5.1.2 Research contribution

##### ***Complexity and product architecture***

In previous years numerous studies have been conducted aiming at analysing and evaluating complexity which arises in the product range of manufacturing companies. Samy et al. (2012) define complexity as “a measure of how product variety can complicate the production process”. In the same concept Arteta et al. (2004) point out that complexity is preventing a company from changing its organizational structure, processes and products, and it is connected to the interrelationships of the system components (Arteta and Giachetti, 2004). MacDuffie et al. (1996) quantify product complexity to test the impact of product variety on quality and productivity in a LEAN manufacturing environment (MacDuffie et al., 1996). Several researcher have performed similar work (Fisher and Ittner, 1999; Fujimoto et al., 2003; Martin and Ishii, 1996), where the focus has been to measure how the production process is affected by product complexity, related to the increasing number of variations. An approach widely used for measuring systems complexity is based on entropy measure (Arteta and Giachetti, 2004).

##### ***Method for ABC differentiation***

The ABC analysis was initially developed by Pareto (1971) has been further used in operations management (Pareto and Schwier, 1971). The product categorization to A, B, and C products is based on the relative distribution of cost or the usage of the SKUs. The multiple criteria of ABC product prioritization is moreover considering several aspects which the

operations management domain have been of great importance for inventory management, such as lead time, substitutability and variability (Beamon, 1999).

With the rapidly increasing number of variants in the recent years, manufacturers are trying to maximize the variants offering, in order to serve their customers' needs, increase competitiveness and identify the market niche. However, not all variants contribute to the net revenue neither at the same percentage. As a result large product variety does not imply for stable long-term profitability (Koo et al., 2009; Sarkis, 1997), and the ABC product differentiation becomes imperative. To this end, later studies have shown relations between the ABC product differentiation and the lot size (Yücel et al., 2009) (Yücel et al., 2009) or substitution (Hsu et al., 2005).

### ***Substitution at different stages***

Substitution is a method which complies with Mass customization principles and platform designs. Current research has classified two aspects of substitution: firm-driven and customer-driven. This research is primarily focus on firm-drive substitution at a module level, as the customer-driven substitution cannot be controlled. The sales person, or even the customer himself, decides on the substitution of one final product with another (Zhou and Sun, 2013).

Zhou and Sun (2013) developed a model to determine the optimal component quantities in an assembly-to-order system with component substitution, so as to maximize manufacture's profitability. Several researchers have considered product substitution based on the demand. Yaman (2009) creates a model in order to define the lot sizing problem by substituting the products of low quality with high quality products (Yaman, 2009). On the other hand, Hsu et al. (2005) develops algorithms in order to define the lot size between two products. The product in lower demand can substitute the product higher demand, with or without the need for redesign.

### ***Lot size and sales demand***

Masuchun and Masuchun (2008) have created a model to determine the optimum lot size in order to match the production flow and the customers' demand (Masuchun and Masuchun, 2008). Bottleneck machines affect the production rate, and in order to maximize efficiency the lot size should be large (Koo et al., 2009). Furthermore, Brynjolfsson et al. (2011) examine the production lot size in relation to the demand (Brynjolfsson et al., 2011). Benjaafar and Gupta (1998) are suggesting that the number of final products and the lot size are commensurate (Benjaafar and Gupta, 1998), however they results are based on the assumption that the production facility is able to expand or change.

### ***Research aim***

Based on the previous literature review, this paper attempts to contribute to the quantification of the relationships between product complexity and lot size. The factors taken into consideration are product common features on module level, substitution on component level and lot size determination. Drawing upon the basic idea of mass customization, a concept is presented where the final product variation is not to be decreased and for short and mid-term planning the production facility is considered under the limitation of neither expansion nor change. The ABC categorization approach is used to determine the appropriate components' substitution strategy, as well as the lot sizing.

The purpose of this paper is to examine the production flow optimization by adapting the product assortment. The previous research has shown the dependencies between the two aspects, however this paper examines them from another perspective. The product mix is the variable, while the operation flow is standard. Due to limitations on expansion of stock and number of machinery, the impact of the product assortment adjustment is used to measure productivity. Additionally, production size should not be affected.

### Proposition 1 (P1)

Substitution on a module and component level contributes to improving of the production flow and capacity utilization of machinery and inventory.

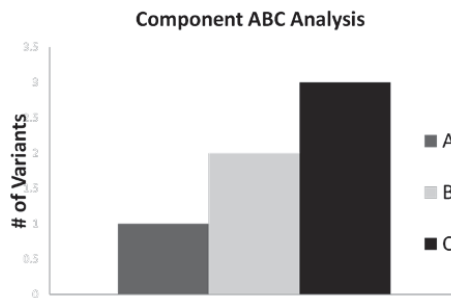
#### *Suggested approach*

##### **ABC product categorization**

Based on the Pareto theory, an ABC analysis on component level is performed, where the sales volume of finished products is used to differentiate between the categories. In detail, 80% of the sales correspond to fewer products, which are considered as A products. Similarly, 15% of the sales volume corresponds to the B products and 5% to the C products .

Sales values are often stored on a final product level. To be able to perform the ABC categorization on components level the variance decomposition structure is used. Each finished product is broken into its different components, based on the listed Bill-of-Material (BOM). The sales volume of the finished product indicates whether the product is A, B, or C. Through the variance decomposition analysis, the sales volume of the components is set in relation to the sales volume of the finished product.

The variant categorization is to be further used in order to implement the two-way substitution.



**Figure 4-31: ABC analysis on component level**

#### ***Substitution and process flow***

The second aim of the research methodology is to implement a substitution method in order to measure the impact on the machine and stock utilization, which is related to the lot size. The suggested approach is based on the theories discussed in the literature section; however it goes one step further by combining the substitution methods for which a two-way substitution method is proposed.

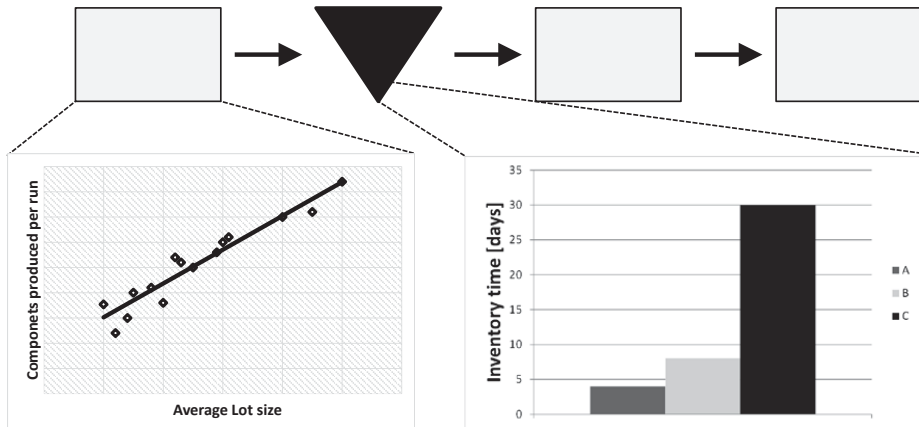
The first step of this method focuses on utilization of the C component variants kept in stock, in order to increase their utilization and free up the stock capacity. C components have by definition lower sales volume. They are taking up more space in the stock and for a longer time period, than the A components, which are used frequently. Moreover the average lot size of the C products is small, which is related to increased changeover and set up times, implying for increased cost and complexity in the production flow. The quantification of the stock capacity is calculated based on the average number of pallets occupied by each component in stock. The machine utilization is calculated on the number of components produced per run.



According to the suggested method, the C components kept in stock would replace the similar components in the A products. The main challenge is to identify which C variants could substitute the A variants in the final product assembly, without compromising neither the quality nor the specifications of the finished product. This first method can be seen a short-term suggestion, with a focus on achieving immediate impact in production

The second step of the substitution method proposes a long-term solution, in which the A components substitute the C components in the final product. This results in out phasing the C components of limited utilization, which leads to an increase of the stock capacity. At the same time the replacement of C components enables higher production and stock utilization of the A components, as manufacturers can plan with higher lot sizes. This action results in optimizing the machinery utilization, especially for those machines that are potentially creating bottlenecks. The optimization is succeeded by reducing the change overs and the setup times for producing A components. In relation to the stock capacity, the substitution of the C components has positive effects, as the slow moving pallets with C components are replaced by pallets with A components.

This step of the suggested approach identifies the relations between the substitution and changes in the lot size, and their impact on the production process.



**Figure 4-32: Impact of lot size on machine utilization and stock**

#### **Lot size and capacity utilization**

The third step of the suggested approach, builds upon the previous and examines the relation between lot size and machine utilization. The reviewed theories indicate a connection between the lot size and the optimization of output of each machine in the production process. The bottleneck machines are of great importance in this stage. Additionally, the lot sizing is related to the second step of the substitution method (A components used for C variants). As the total volume of the A components increases, the manufacturer can plan with a higher average lot size of the process flow will. The examined relation is illustrated in the following figure.

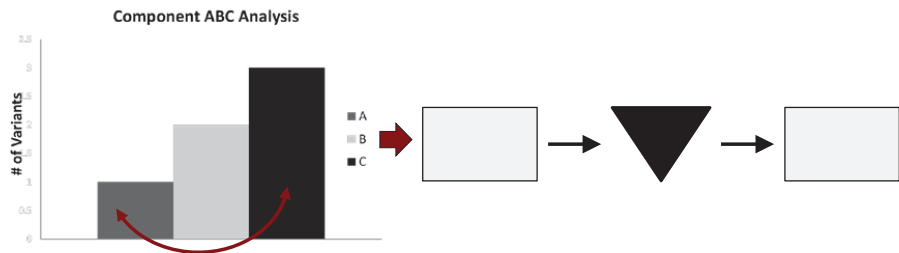


Figure 4-33: Impact of substitution strategy to the process flow

**Case study**

In order to test the proposed framework and quantify the production flow optimization by adapting the product assortment, a case study of a manufacturer in the CTO industry is performed. The company produces plaster gypsum boards for the construction industry. The final product consists of several layers (components): plaster façade (with or without paint), gypsum board, light reinforcement, heat and fire insulation. The challenging aspect of this specific case study is the lack of expanding options, especially on large scale such as expansion of the production site or the warehouse, purchase of supplementary machinery. As a result the chosen case study is selected as an example where the optimization of production flow and capacity utilization could only be achieved by the examined proposition. Empirical data were gathered on a daily basis for one-month period, and the forecasted increased demand in a two-years' time period. The data sample regards all product orders and the related daily activities in machine and inventory utilization. Data collection included also the modular structure of the products in terms of assembly processes and stock capacity utilization.

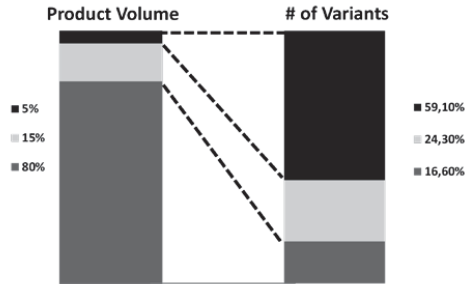
In order to implement and evaluate the suggested approach on this case study, the analysis of the current state is to be used as a baseline. The following table summarizes the data required for the analysis.

Table 4-12: Research protocol

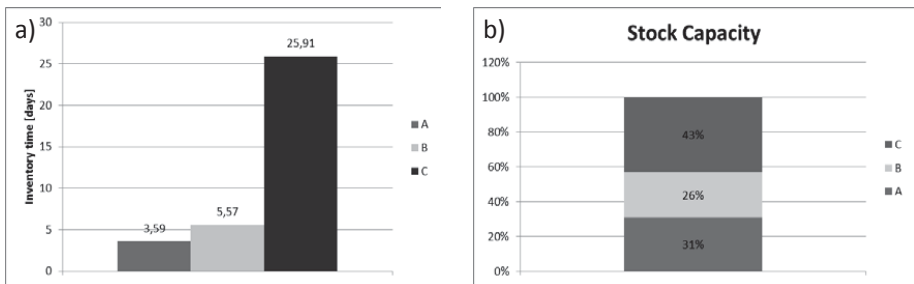
Data needed	Quantification
1. Bill of material of finished products Sales volume of finished products	ABC analysis on the component level Substitutability on the component level
2. Average lot size per run per component Production per run per component	Calculation of the optimal relation between lot size and machine utilization
3. Number of pallets with C components in stock Number of pallets with A components in stock	Stock utilization caused by substituting C components with A

Implementing the suggested approach, an ABC analysis was performed to the finished products, and subsequently to the components. The following figure illustrates the relation between the volume of the finished products and the number of variants, based on the ABC product differentiation made after the related data was acquired.

Table 4-13: Percentage of finished products and of their variants



The analysis of the current state constitutes the first step of the proposed framework. to the historical data on sales volumes helps to estimate the current market trend and indicates in which steps of the production the capacity exceeds the maximum level, both in machinery and stock keeping units. The current state is used as a baseline scenario and serves when evaluating the alternative solutions. The first scenario suggests substituting C variants with A variants on component level, i.e. at an early stage of the production process. In this case study, the results from the early component variant decrease through substitution lead to a reduction both in stock capacity requirements, as well as in the bottleneck machines. The following figure shows the average time for the A, B, and C components kept in stock. C components have in average 20 times more inventory time than A components. Due to this ratio, by eliminating C components the stock capacity will increase rapidly.



**Figure 4-34: a) Duration of stock keeping per ABC component and b) Percentage of stock capacity per ABC component**

Based on the number of pallets in stock for each component, the following figure clearly illustrates that C components require higher capacity, due to the fact that they are slowly moving. C components take overall 43% of the available storage space. By substituting the C components with A, the storage space will become available for A components, which will also lead to increase the production of A components.

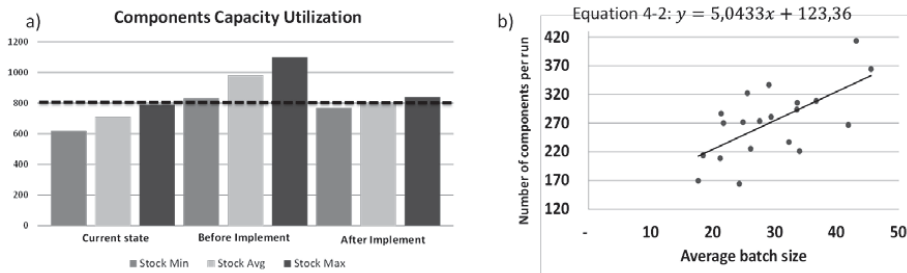
The second scenario consists of a combined short and long term solution, with two-way substitution at a later stage in the production process. The first step suggests the substitution of A variants by C variants, in order to reduce the number of the slow moving C variants in stock. This approach could be applied due to fact that the substitution will not jeopardize the quality of the final assembly, as for the case products the only difference between the two variants is the size of components (length, width). As a result the variation of the final products would not be affected. The second part of this scenario is the long term suggestion, which introduces substitution of C components on the final products by A. The substitution takes place at a later stage of the final assembly. The outcome of this scenario is a great

reduction of stock capacity requirements, as the slow moving C variants are no longer produced. This strategy results in freeing up the space occupied by C variants and providing more space for the widely used A variants.

**Table 4-14: Summary of substitution strategies**

	C plates for A cores		A plates for C cores		Both strategies	
Total variants		618.8		618.8		618.8
Total eligible c plate variants		137.8		24.7		149.5
Total variants %		28.9%		5.2%		31.4%
Total pallets		83.96		14.97		92.70
Total pallets %		10.2%		1.8%		11.3%
Total cost	€	192,649.05	€	181,933.90	€	374,582.95
Cost per pallet	€	2,982.82	€	15,796.66	€	5,252.86

The following figure illustrates the capacity utilization for the components kept in stock. Three scenarios are compared, the current situation, the future state (in two years) without making any changes and the future state after implementing the suggested approach. The result shows that by substitution of C components with A, the Average stock capacity will not exceed the maximum limits.



**Figure 4-35: a) Capacity utilization for components and b) Relation of lot size and production**

With reference to the machine utilization, the following figure illustrates the relation between the average lot size and the number of components produced per run. The tendency is quantified to the following formula:

**Equation 4-2: Relationship between batch size and components in production**

$$y = 5,0433x + 123,36$$

The figure above indicates that the machine utilization benefits from the increasing lot size. The number of components produced per run is directly depended on the lot size. This implies that for the A components, where the production is high, the optimum lot size should be increased.

#### 4.5.1.3 Conclusion

With this study a practical framework for reducing the complexity level at different stages in production is presented. An ABC categorization based on sales volumes has been used to distinguish between slow running and fast moving components, while BOM structures of final products have been analyzed to identify the sales volumes components and modules. A two-way substitution has been used on different stages during production and its impact on lot sizing and capacity utilization for machinery and storage space has been discussed. The framework was tested on a case study, where a CTO manufacturer has been challenged

with an increased customization demand and limited production capacity. Based on performed analysis, the impact of a number of complexity reduction scenarios was quantified in relation to total production cost and utilization, which gave further insight into how such architecture changes may be quantified in detail.

Thereby, the now established detailed insight into the monetary effect of possible complexity reduction strategies accommodated answering the last research question.

**RQ3.5:** How can the complexity of ETO architectures in MC be assessed and managed?



## 4.6 Chapter summary

Drawing on the literature review in Chapter 2 and Chapter 3, this chapter provided new insight into the application of MC in ETO industries. Eleven research subjects were in total evaluated, consisting of relevant literature reviews complemented with eleven case studies and one survey. Organized in four main areas, the chapter provided an exhaustive theoretical and empirical investigation of subjects relevant for answering the research questions. First, the defined general MC capabilities were assessed through a proposed method, comprising the investigation of variability in CMs and pre- vs. post calculations. The results navigated the development of capabilities towards the strongest potential for improvement (Section 4.2). Next, the development of an effective and efficient choice navigation capability was investigated (Section 4.3). The conducted studies elaborated based on three different scenarios how a CS could be used to support the specification process of ETO companies. In accordance with the formulated capability definition, configuration systems should be planned with a well-defined scope. This scope would target the most essential “need to have” aspects first, then gradually expend the functionality of the system to increase efficiency. A method for making a systematic plan was formally discussed and demonstrated on a practical case.

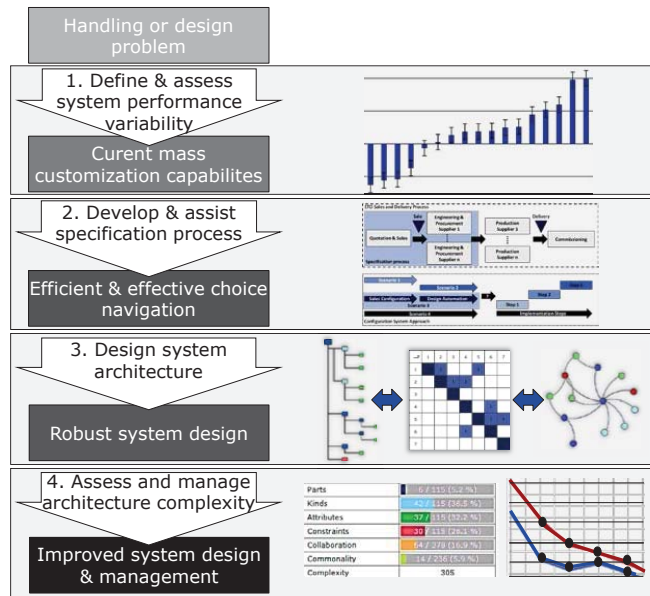
In addition, four feasible scenarios for a configuration system support were demonstrated. Section 4.4 deals with the development of a robust system design. Depending on the company situation, this may comprise partly or entirely the customization value-chain (see Section 1.2.1.1). Based on an initial clarification of suitable architecture design strategies for ETO companies through a survey investigation, four additional research studies were conducted. The studies included important aspects of architecture design and management, relevant for answering the third research question *RQ3*. This inter alia included the investigation of platform design and preferred architecture for MC, a definition of feasible a two-dimensional postponement strategies, a cost-benefit analyses, and a formal computational architecture synthesis using structural measures for architecture management. Finally, in Section 4.5, an initial study on the improvement of system design and management was conducted. A detailed method was proposed for the reduction of system complexity through substation strategies causing a reduction of variety and an increase in commonality.

# 5 CONCLUSIONS

This chapter summarizes and concludes the thesis. In Section 5.1, the answers to the main research questions including their sub questions developed throughout the thesis are summarized. Their contribution is presented using a reference framework.

## 5.1 Key findings and research contributions

The key finds and the corresponding research contributions of this thesis are summarized through the answers to the three research question and their sub questions stated in Chapter 1. This is organized according to a reference framework illustrated in Figure 5-1 which represents the main research areas executed in a proposed sequence.



**Figure 5-1: MC reference framework for ETO industries**

**RQ1:** How can the transition process of ETO companies moving towards MC be supported effectively?

RQ1 refers to an effective way of supporting the transition process towards MC through the assessment and development of general MC capabilities, as illustrated in *Stage 1* in Figure 5-1. The question includes two sub questions, which will in the following be summarized.

**RQ1.1:** What general capabilities should ETO companies develop when implementing mass customization?



The answer to *RQ1.1* includes a review of key publications and the investigation of relevant subjects from literature related to operations management and engineering design (Chapter 2 and 3). Moreover, the established understanding was tested throughout the empirical investigation (Chapter 4). The main contribution of this answer can be summarized as follows.

1. *Detailed understanding of general capabilities*: Based on an extensive literature review of key subjects, this thesis established a detailed understanding of 5 general capabilities relevant for successfully implementing MC in engineer-to-order companies (Chapter 2 and 3). The first capability refers to the establishment of an efficient and effective choice navigation, which is described in the context of developing and assisting specification processes. The remaining three capabilities refer the design of a robust system architecture, consisting of product, process and logistic domains. Each domain includes a number of comparable qualities.
2. *Empirically validated significance*: The importance of the capabilities was confirmed throughout the subsequent empirical investigation (Chapter 4).

**RQ1.2:** How can the quality of such general MC capabilities be assessed and their development be further directed?

The answer to *RQ1.2* comprises the conceptual design and further development of a performance assessment method and its application on three case studies across there different industries.

*Conceptual design and refinement of a performance assessment method*: based on theoretical and empirical evidence related to the varying profitability of ETO variants, a concepts for a method identifying the cause of the variability was developed. The concept was initially tested on a practical case and the results were used enhance the approach and to establish a more systematic and thus stepwise investigation of the occurring variability. The investigation of high and unexplainable variability in CMs and pre- vs- post-calculations determined the suggested enhancement of any of the MC capabilities. Hence, at the end of this *Stage 1*, the current MC capabilities have been evaluated, which ideally determines the scope for a further investigation.

**RQ2:** How should the specification process of ETO companies moving towards MC be developed?

The answer to this question *RQ2* referred to the investigation of three subjects related to postponement, potential use of CSs and their practical implementation. The question relates to *Stage 2* of the reference framework and was answered based on the corresponding sub questions.

**RQ2.1:** How can postponing the customer order decoupling point be enabled and how does it affect the specification process of ETO companies?

**RQ2.2:** What are expected benefits, risks and limitations when implementing CSs for ETO products?

**RQ2.3:** How should CSs be used to assist the specification process in ETO companies?

The answers to the sub questions *RQ2.1*, *RQ2.2* and *RQ2.3* comprise a review of essential publications and empirical study addressing the obtained insight. The main contribution can be summarized as follows:

1. *Comprehensive understanding of the effects from implementing CSs*: Based on an initial understanding from literature (Chapter 2), RQ2.1, RQ2.1 and RQ2.3 were addressed by conducting several case studies, both in the *Descriptive Study I* as well as in the *Descriptive Study II* phase. The investigation demonstrated the potential of an adequate use of configurators. State-of-the art configurators combined with other IT systems, such as CAD or MathCAD, are capable to assist aspects of the specification process. When postponement is not employed properly, the support of detailed design activities (making drawings) can free up a severe amount of engineering capacity. On the other hand, if postponement in the engineering dimension is implemented, even higher effects are to be expected, leading to additional benefits for customers. In such cases, there are different possible scenarios for a stepwise implementation. For highly complex architectures, it was particularly important to establish a well-defined plan (scope) for the CS support, to facilitate a greater scale and depth of the implementation.
2. *Systematic literature review and exhaustive empirical investigation on CS benefits, risks and limitations*: In addition to the performed case studies, RQ2.1 was answered through systematically studying key publication addressing the topic and qualifying their results. Moreover, the empirical study on a broad range of firms using CSs (based on S1) was used to validate the understanding of the way how the software is used in praxis (*Descriptive Study II*).

At the end of this *Stage 2* of the reference framework, an efficient and effective choice navigation capability is developed.

**RQ3:** How should architectures for mass customizing ETO products be designed and managed?

The significance of architecture design for the success of MC was elaborated throughout the thesis. This question refers to the design and management of the system architecture as illustrated in *Stage 3* and *Stage 4* of the reference framework. The answer to this comprehensive question was organized in five sub questions, which were successively addressed in the course of the research project.

**RQ3.1:** How can architectures user for mass customizing ETO products be described explicitly and visibly?

**RQ3.2:** What is suitable architecture design strategy for mass customizing ETO products?

**RQ3.3:** How can a consistent architecture design process for MC be organized?

**RQ3.4:** What are preferred architectures for MC and how can they be formally described?

**RQ3.5:** How can the complexity of ETO architectures in MC be assessed and managed?

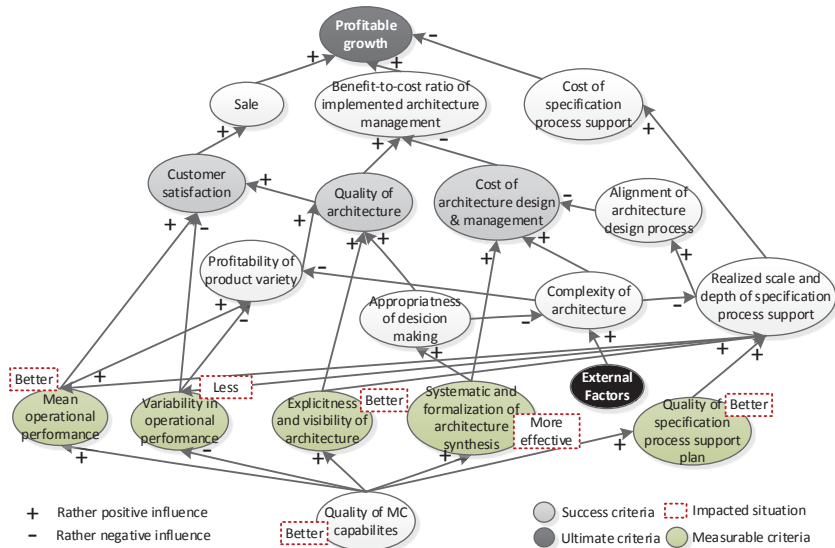
The answers to the sub questions RQ3.1 to RQ3.5 comprise an exhaustive review on related topics (Chapter 3). The established understanding was refined and supplemented with five detailed studies. The main contribution can be summarized as follows:

1. *A list of requirement for architecture synthesis of product families*: Drawing on a detailed evaluation of the architecture design process (Section 3.1.2), a comprehensive discussion on requirements for an architecture synthesis of product families was conducted (Section 3.1.3) and nine major requirements were presented (Table 3-1). The requirements can provide guidance for creating an consistent architecture design process for MC, leading to an better alignment of the customization domains. Thereby, the answer to RQ3.3 was provided.
2. *A modelling method describing product family architectures for MC in an explicit and visible way*: Based on the established requirements for architecture synthesis and a detailed investigation of possible modelling methods, a modelling method was presented, meeting these requirements (Section 3.4). The modelling method was tested and refined through four case studies, thereby answering RQ3.1. The suggested method is based on established modelling techniques, including the PVM, DSM and node-link diagram. It combines them into a consistent framework, to overcome their individual limitations.
3. *Exhaustive investigation of architecture design strategies*: Drawing upon key publications in literature (Chapter 2), an extensive empirical investigation of 18 companies (based on S1) using CSs was performed, to enhance the understanding for a suitable architecture design strategy for ETO products. The results proved that a systematic development strategy, which includes the development of an analysis model, a design model and a computer model is preferable for ETO firms dealing with complex architectures and little explicit documentation support. Thereby, the answer to RQ3.2 was provided.
4. *In depth evaluation and development of structural measures for architecture assessment*: Based on the identification of preferred architectures for MC (Section 3.1), a list of structural measure formally assessing the quality of architecture for entire product family was developed and empirically tested (Section 4.4.5), thereby answering RQ3.4.
5. *Development of a practical tool for architecture design and management*: To support the design and management of complex architecture, a modelling tool, termed IDM, was developed as a pragmatic and directly implementable solution in form of an Excel add-in. The tools was developed following the described aspects of visual analytics (Section 3.5.2), thereby providing an intuitive and interactive way to interact with complex architectures. The tool was complemented with additional software (parser), to transfer architectures modelled in CSs, hence to overcome their limitations (Section 4.4.5). Finally, the IDM tool was implemented on a practical case (*Descriptive Study II*).
6. *Conceptualization, development and application of a generic complexity management approach*: Based on elaborate review on literature dealing with complexity, a definition of complexity was provided in the context of systems and architectures (Section 1.2.1.4). Next, different complexity assessment and management approaches were identified and a generic and comprehensive approach to complexity management was conceptualized (Section 3.5.1). Measures describing complexity were included in the IDM tool, making an assessment of any architecture changes to complexity possible in praxis (Section 4.4.5). Aspects of the generic approach were initially tested on a practical case (*Descriptive Study I*), were a detailed monetary impact on complexity reduction of a production architecture was identified through a developed method (Section 4.5). Thereby, the answer to RQ3.5 was provided.

Finally, with the performed *Stage 4* of the reference framework, an improved system design and management is supported.

## 5.2 Research evaluation

This section reflects on the evaluation of the conducted research. The research project was to a considerable extent grounded in the discipline of engineering design. Petersen et al. (2000) present a structured framework for the evaluation of related research work. The framework is applied on the measurable criteria formulated in Section 1.3.4 (Pedersen et al., 2000). To recall the created network of influencing factors, the impact model is hereby included.



**Figure 5-2: Network of influencing factors (impact model)**

1. *Accepting the constructs validity:* This first stage refers to the acceptance of the individual constituting the method. The authors suggest using established theory, based on which the elements are developed. The individual elements formulated in the impact model are based on an extensive literature review within a broad body of disciplines, which provides a thorough basis for their formulation. As discussed in Chapter 2, assessing the operational performance through mean values is an established approach in operations management. Also operational variability has been mentioned regularly for profitability analysis (Section 4.2). The requirements for an explicit and visible architecture have been discussed based on related literature (Section 3.1). The need for a systematic and formal architecture synthesis was described based on detailed literature investigation (Section 3.1). The quality of the specification process support plan refers to the need of a well-defined plan for implementing CSs. This factor was elaborated based on literature in several stages throughout the thesis, in particular in Section 2.2 and Section 4.3.3.
2. *Accepting internal consistency of the way how the elements are put together in the method:* It is advised to use illustrations to demonstrate the information flow and relationships. The internal consistency of the elements is based on the literature review complemented with the empirical investigations. The relationships of the individual elements was discussed in Section 1.3.4 and references the corresponding investigations were made. By answering RQ1, it was elaborated that the mean and variability in operational performance are a direct result of the *quality of MC capabilities*. Furthermore, the answers to RQ3 provided the link to the developed *explicitness and visibility of architectures* and to *systematic and formalization of architecture synthesis*. On the other hand,

the answers to RQ2 elaborated on the *quality of specification process support* plan as an essential element for developing *efficient and effective choice navigation capability*.

3. *Accepting the appropriateness of the example problems chosen to verify the method performance*: This is suggested to be done by documenting that the example problems are similar to the intended application area, that the found problems represent the actual problems for which the method is intended and that the data can support a conclusion. The exhaustive empirical investigation facilitated testing and refining the methods within cases relevant for the actual problems. Their practical application and acceptance demonstrated the managerial relevance, while their publication proved the theoretical relevance.
4. *Accepting that the outcome of the method is useful with respect to the initial purpose for some chosen example problem(s)*: Representative examples are suggested to be used to state the usefulness. Usefulness can for example be linked to reducing cost, time and/or improving quality. The representative examples directly affected measures like cost and lead time, effectiveness, thus indicating a useful outcome. The detailed results are described in each paper in Chapter 4.
5. *Accepting that the achieved usefulness is linked to applying the method*: It is suggested to evaluate each element individually. Here, each method was derived based on methods, which are established and proven for usefulness in existing literature. The methods have been further refined and tested on the empirical examples, indicating a link to the applied method.
6. *Accepting usefulness of method beyond example problems*: this stage can be achieved after the previous stages have been accepted, thereby claiming generality. In operations management domains this is often referred to 'external validity' through analytic generalization (Yin, 2003). The hereby developed research was based on an extensive literature review and a broad empirical instigation across different industries. The major part of the research questions were addressed in *Descriptive Study I* further in *Descriptive Study II*, hence it may be fair to claim that there is a potential for generalization. However, since the discussed context is rather encompassing, a more acceptable claim may be to state that the presented construct was as a whole tested in an initial state, referring to the described fifth stage of the DRM framework (see Section 1.3.2).

## 5.3 Research limitations

The underlying methodological implications of this research should be acknowledged as research limitations, as summarized below:

1. *Scale vs. scope*: This research was undertaken as an applied research project within the Operations Management research group together with the Division of Engineering Design and Product Development of the Technical University of Denmark. The related diversity of stakeholders from industry and academia determined the broad research scope, making it difficult to perform in depth and repeatable tests of the developed methods and tools. This limitation can be gradually overcome by expending the tests on more case studies and thereby improving the applicability of the methods and tools continuously. At the same time, the strong research network created enormous opportunities for investigating a variety of research subjects. In result, a comprehensive overview over relevant themes was developed and additionally complemented with a high number of empirical studies.
2. *Unavoidable subjectivity*: The proposed themes for investigation (See 1.2.3) were mainly based on literature and supplemented through discussions with researchers, supervisors and industry experts from the researchers network. This naturally presence of bias was attempted to be overcome by engaging in discussions during the attended seminars, conferences and external research stay. However, it is reasonable to believe that a certain degree of subjectivity has influenced the research direction as stated in Section 1.3.1.

## 5.4 Opportunities for further research

Future research work may include:

1. *Full industrial evaluation of the reference model*: Ideally, the reference model presented in Section 5.1 should be tested entirely on one or more selected product families. Since the identified MC capabilities are interrelated, it is expected that the combined development of the capabilities would as a whole outperform the sum of the individual benefits. Due to the wide-ranging change within the organization of companies and the related time frame, such study may be performed initially on less complex product families and then gradually extended.
2. *Full application of the generic complexity management framework*: The developed framework could only be tested initially on a limited number of case studies. Despite the promising results, it would be beneficial to apply the entire model on a selected industrial case. In particular it would be relevant to investigate the quantification of variant profitability instead on a consolidated level based on mean project profitability, on the more detailed product variant level. However, experience from applying the analysis on complex ETO architectures indicated that this may be difficult to achieve, due to the following reasons: (1) data on time and resources spend within engineering activities often not available or not reliable, (2) the architecture complexity may result in a commercial variety tending to infinity, making any investigation of variant profitability without an IT support tool such as a CS infeasible, (3) the scope of the CS support for complex architectures is typically limited with respect to detail and coverage, reducing the possibility for any detailed profitability analysis.
3. *Extension of the IDM tool*: the IDM tool may be extended with automatic clustering and sequencing algorithms to exploit the full potential for architecture improvements based on structural measures. However, such algorithms still need to be developed, as existing ones are bounded by applications for single product models. Moreover, the amount of computational power required for executing the algorithms would extend both the current capabilities of conventional computers and the capacity of Excel, reducing the practicality of the chosen solution.



## 5.5 Concluding remarks

Overcoming the customization-responsiveness squeeze is essential for many consumer and ETO industries alike. Its handling comprises several risks, including rising complexity and reduced profits, whereas an adequate management offers enormous opportunities. MC provides such a promising approach to the efficient and effective handling of the customization-responsiveness squeeze. While for traditional mass markets, this paradigm has gained an enormous attention, its application on ETO products has been limited.

Based on a comprehensive state-of-the art literature review of research within operations management and engineering design, the thesis contributed to an enhanced understanding of this interdisciplinary area. The theoretical investigation was comprehended with insights from a survey with experts from 18 manufacturing companies. The gained results determined the conduction of eleven additional case studies, to develop an embracing concept for the enhancement of general MC capabilities. The concept was detailed into methods assessing the identified MC capabilities, followed by architecture design and complexity management methods. Several advantages of the methods were emphasized and further improvements were suggested. Furthermore, an executable tool termed IDM was developed, to apply a proposed formal computational structural analysis method. The IDM tool employs aspects of visual analytics to create an interactive and insightful modelling environment. The tool was applied on a practical design problem, where it was connected to an advanced configuration system, to evaluate its usefulness in industry.

The author is confident that this thesis improves the current understanding of MC and its possibilities for a successful implementation in industry and trusts that the developed concepts, methods and tools will inspire academic researchers and practitioners for further research and development.

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# 7 APPENDICES

## APPENDIX A



# Analyzing the Accuracy of Calculations When Scoping Product Configuration Projects

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**Abstract.** Product configurators have increasingly been applied in industrial environments. With their help, companies providing customized products have managed to redesign their specification processes and to better handle the growing product variety. But despite the promising benefits, conducting configuration projects is still challenging. Assuming that configurators would naturally solve the existing flaws, both, researchers and professionals typically neglect the need for a making a precise scope for their implementation. Based on this theoretical and practical concern, the present study provides a detailed framework on how the highest potential and eventually the most benefits from using configuration systems can be identified. In particular, this paper investigates how the less explored domain of varying gross margins and calculations reveal a considerable potential for improvement by means of configuration.

**Keywords:** Product configuration, Configurator development, Sales configuration, Price calculation, Gross margin.

## 1 Introduction

Implementing mass customization strategies has helped organizations to meet this “customization-responsiveness squeeze” [8] and whilst to produce and to offer customized products with a reasonable high quality at nearly mass production prices [25]. To this end, industrial companies have been challenged to reorganize their way of doing business [3] in multiple dimensions. At the same time, a constantly growing product variety has lead to an increasing complexity of products and processes and thus to the need to better coordinate the way product specifications are performed [8].

The development progress of IT systems has enabled engineering-oriented companies to increasingly implement software-based expert systems, such as configuration systems, to support the product specifications of complex products [1]. Eventually, a growing number of successfully implemented configuration projects have been studied, where organizations have significantly improved their operational performance [7]. The thereby achieved positive effects typically address a series of implications, such as reduced lead times, fewer specification errors and better knowledge sharing and knowledge representation [1, 6, 7-10]. But while there are doubtlessly several advantages of using

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configuration systems in an engineering-oriented environment, when starting configuration projects, several risks need to be considered:

1. Since performing configuration projects is a rather complicated task [1, 20], it is difficult to anticipate the accruing development and implementation costs beforehand. If for instance a project turns out to be more costly than initially expected, the risk of failure would be relatively high, as the management board might no longer be willing to support the investment.
2. Implementing a configuration system usually affects the internal workflow of an entire firm, starting from the sales to the production department. Reorganizing established workflows would then typically demand significant changes in the business process of organizations, where configuration systems have to be widely accepted and used. If the resistance of change thereby outranges the promised benefits, the configuration project is very likely to fail [1].

In order to keep the risk of abandoning a planned or even initiated project down, companies should focus on identifying the highest potential and eventually the most benefits from using configuration systems. After all, defining the scope is crucial for the success of the project, as an effective (doing the right things) and efficient (doing things right) approach for product configurations is becoming a highly relevant way on coping with rising complexity, whether organizational, product or process related. This paper therefore deals with the question on how to define a suitable scope for implementing configuration systems, which reveals the highest benefits for project implementation and the least risks for project failure. To answer this question, after introducing the research methods (section 2), the first part of this paper (section 3) provides a brief overview on existing approaches for the development and implementation of configuration systems, based on which a new framework is introduced. The second part (section 4) refers to an industry case, where the developed ideas are directly tested for relevance and their assumptions are verified. The achieved results (section 5) are then analyzed with the aim to reflect on the previously developed hypothesis. A final conclusion is drawn in section 6, where the most important findings are summarized.

## 2 Research Methodology

The research methodology applied in this paper is following an action research approach, where the researcher is actively involved in a transformation process on a real case and is thereby achieving scientific contributions [30]. This type of methodology requires separating the development procedure of the performed application (i.e. the industrial project) from the development methodology (i.e. the scientific contribution). Based on a foregoing literature study, the created ideas are applied on a collaborating partner, an Engineer-To-Order (ETO) manufacturer in the Danish precast construction industry. Since the construction business is a very complex environment, where only little IT tools have yet been widely applied [31], the industry is a particularly interesting research field for developing and testing out new ideas.

By including the cooperation of the industry case in the development process, the authors believe that more stable results can be implemented at a faster pace. To ensure the rigor of the data collection, first, qualitative methods (e.g. unstructured or semi-structured interviews, workshops and discussions, notes and observations) are used and help to achieve the required knowledge background. Inspired by the machinery industry, product and process modeling tools are hereby applied to qualify the operational performance and product complexity. Then, quantitative data is collected and analyzed to obtain triangulation of the gained insight.

### 3 Literature Review

#### 3.1 Effects from Product Configuration

The literature dealing with the development and implementation of configuration systems suggests a number of ways on carrying out configuration projects in a systematic way [10, 26]. The majority of the studies is thereby focusing on defining the right development and implementation procedure, while only few of them investigate possible strategies for developing product configurators [1]. Either way, once projects have been initiated, a well defined framework for developing configuration systems obviously helps project leaders and domain experts to follow predefined phases, to employ best practices, established tools and suitable modeling techniques.

Table 1. Benefits from using product configuration systems

Potential Benefits	Author											
	Ardissono [6]	Blecker [21, 27]	Forza and Salvador [7-10]	Haug [1, 11-12]	Helo [18]	Hvam [13-14, 23, 26]	Song [15]	Tenhilä [16]	Trentin [17, 22]	Tiihonen [24]	Tseng [28]	Yang [19]
Shorter Lead Times	x	x	x	x	x	x		x	x	x	x	x
Improved Quality of Product Specifications	x	x	x	x	x	x		x	x	x		
Better knowledge preservation			x			x			x		x	x
Fewer resources for product specification	x	x		x	x	x			x	x	x	x
Less routine work during specification process		x		x	x	x			x	x		
Less time for training new employees				x								
Improved delivery calculation	x		x	x		x		x				
Improved handling of product variety	x	x	x	x	x	x	x			x	x	
Improved order acquisition		x	x	x	x	x				x	x	
Less quotation to order deviation				x		x						
Fewer resources for quotation process		x	x	x	x	x						
Reduced complexity in the specification process	x	x	x	x			x			x		x
Better product quality			x					x	x			
Better adopting new products and processes						x			x			

To give reasons and justification for conducting configuration projects, academia usually limits to proving the benefits from using already successfully implemented systems [1, 20]. To this end, apart from a number of well described case studies [11-14], more recently extensive surveys have been conducted [17, 22]. Table 1 above lists a sample of the research dealing with mapping the benefits for engineering oriented companies when using configuration systems to support their business. As illustrated, the studies propose a series of benefits which companies potentially gain from using configuration systems. In most of the cases, they are directly related to the operational performance of organizations, which in an operations management domain concerns const efficiency, quality and delivery [32].

However, little attention has yet been paid on how to efficiently meet the wide-ranging challenges that need to be overcome when initially considering the implementation of configuration systems. To confirm the improved performance quantitatively, researchers mainly analyze the lead time performance and the quality of the specification process. While for the first aspect, management tools such as a Gap Analysis or Value Stream Mapping (VSM) have been suggested [12, 14], the latter aspect has been less examined [22]. A reason for that can be that in general quality can be defined in several ways [26]. Crosby (1980) for example approaches the term from four viewpoints, as he addresses the conformance to requirements, prevention, performance with no defects, and the price for non conformance [33].

Considering this multidimensional perspective to quality, it is eventually much easier to measure the lead time performance of an organization, than the quality with which specifications are done. Thus apart from counting the defects (errors) of companies' specifications [26], additional analytical methods have to be employed to assure reliable statements about their quality. This implication has even gradually been reinforced by today's business environment, where firms which pursue mass customization strategies struggle with an increase of product, process and organizational complexity.

### 3.2 Quantifying the Accuracy in Cost Calculation

When investigating the economical perspective on how successful companies deliver their custom tailored products and services, it is useful to study the parameters that assess this performance. From a financial perspective, the so called Key Performance Indicators (KPIs) aim to summarize the ultimate results of a business, which may consist of a revenue ratio, gross margin deviation, Earning Before Interests and Taxes (EBIT) and profitability [35-36]. Experiences from collaborations with companies making complex customized products show that the majority encounter significant gross margin deviations [34]. Figure 1 below shows one of the industrial examples, a manufacturer providing customized building equipment, where the actual gross margins (GMs) of completed projects vary between -60% to +50%. The achieved GMs of individual projects have been sorted according to their success, assuming that projects with higher GM would be regarded as more successful.

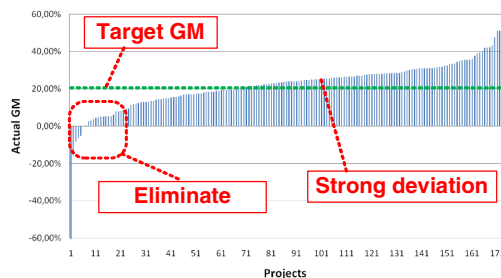


Fig. 1. Gross margin deviation for projects (adopted from [34])

Even though the manufacturer has estimated a 20% margin for calculating all his quotations, the post calculation reveals a very different picture of the obtained GM. No doubt, there might be many reasons why companies are experiencing such a significant variation. But assuming that a relatively fixed GM ( $20 \pm 5\%$ ) is pre-estimated, in general, it can be concluded that unexpected variations on actual GMs result from poorly made pre-estimations on costs for making specifications, manufacturing and for providing services. As indicated in Figure 1, at this point we argue that more accurate pre-calculations help companies to decide on their product portfolio and accordingly to evaluate beforehand which projects are profitable. Better performed estimations would thereby help to improve the quality of specifications and products by means of an improved conformance of the requirements [22]. To fill this gap and to come a step closer to our initial question on how to ensure a successful planning and implementation of configuration systems, we propose the following hypothesis:

**Hypothesis 1:** Investigating the deviation between GMs and pre and cost calculations is positively related to the resulting potential benefits from implementing configuration systems.

### 3.3 Introducing the Framework

To clarify the hypothesis, we introduce a framework for making the right decisions when investigating the most suitable scope for implanting configuration systems. The framework is based on the procedure for the development and implementation of configuration projects introduced by Hvam et al. (2008) [26].

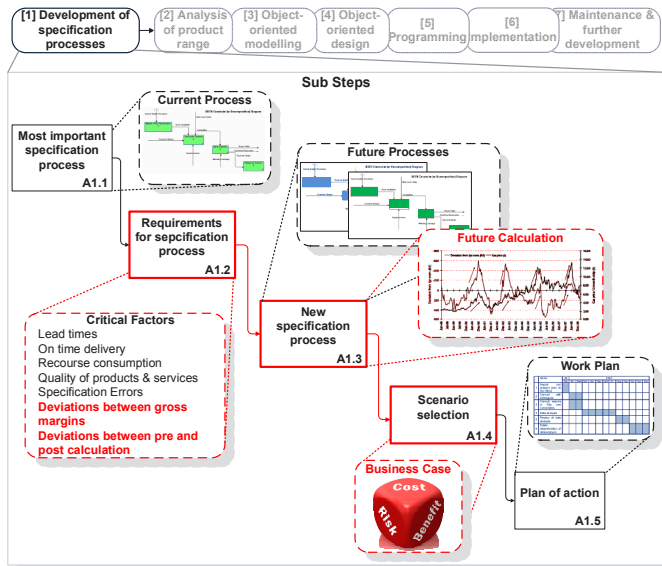


Fig. 2. Development of specification processes

By following the lifecycle of a configuration project, the procedure suggests conducting projects in 7 major phases, starting from the panning phase (development of specification processes) first. The authors argue that at the beginning, engineering companies should investigate the way their custom tailored products and services are specified (order fulfillment) and how the communication to the customer (order acquisition) is organized. Analyzing the specification process would allow firms to draw conclusions on their current operational performance and to uncover vulnerability. The objective of this phase is to develop a better performing future specification process, which is supported by a configuration system.

As illustrated in Figure 2 above, the authors describe this first phase in 5 sub steps, in which well established modeling techniques and analyzing methods are used. In this paper, we draw our attention in particular on the less examined approaches in literature (marked in red). For a more detailed description of the entire steps, we recommend Hvam et al. (2008) [26]. Once the current specification activities have been mapped (step 1), in the next step, the requirements for the future specification process are to be set (step 2). Here, a list of critical success factors may help to decide how to proceed with the analysis. Besides the well described studies on analyzing lead time performances, recourse utilization etc., the less discussed issue of strongly varying pre and cost calculations is further investigated. To evaluate how successful completed projects were and to what percentage the manufacturing costs were affecting these results, the analysis of GMs and the distribution of manufacturing costs is suggested.

In case the KPIs fluctuate stronger than the company's business strategy allows, in the third step, traditionally one or more TOBE specification processes are to be drawn. With the focus on cost calculations, here, we additionally propose TOBE calculation processes and a subsequent business case, where the most suitable scenario is chosen (step 4). Finally, in step 5, a plan of action is to be created ensuring the continuation of the project. Having briefly described the proposed framework, the following sections explain how the methods have been applied on a real case.

## **4 Case Description**

### **4.1 Introducing the Company and the Business Environment**

The studied company is a leading Danish producer of precast concrete elements for buildings, where customized products are offered for various building types, e.g. industrial buildings and warehouses or apartments and offices. Being successful on the market for many years, the company has gained a lot of expertise and working know-how. But because of the changing requirements in the construction business, the company is asked to respond to this dynamic situation efficiently. The manufacturer is intending to redesign its product portfolio and the way it is doing business. However, like in most companies, product development and development of business processes have been planned separately. This is especially common for the construction industry, which is regarded as being a project-based business sector [5]. Here, the product development is typically done in projects, where the individual

products are being developed with more or less random reuse of previous solutions and knowledge.

Being aware of the present challenges, the research group is entering the development process to assist the domain experts and to apply and verify the newly developed hypothesis. Especially the combination of a dynamically changing business environment with low level of automation and IT experience promises many potential research achievements. The gained findings are summarized in the following sections.

4.2 Investigating the Current Specification Process

To improve the operational performance and thereby to reduce the complexity of the business processes, the precast manufacturer is considering the use of IT tools, such as configuration systems. In order to facilitate the success of the planned configuration project (see section 1), a clear defined scope has to be developed. Thus, following the procedure introduced in section 3, in the beginning, the most important specification processes have been studied.

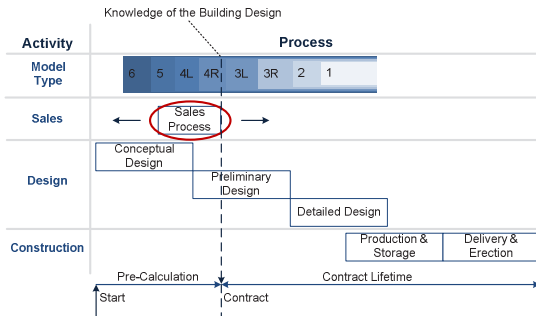


Fig. 3. Main activities in the precast industry

Figure 3 illustrates a high level representation of major procedures in the precast industry, where in addition to the actual design process, common management practices have been established to create “Models” of the same basic processes across the enterprises [3-4]. The contract between a contractor and the precast manufacturer is made on the basis of these models. They determine to what extend the manufacturer is involved in the design process of the building. In “Model 6” for instance, the manufacturer is supporting the design process from the very first beginning, making structural analysis for the entire building based on a given design intent from the architects. In contrast, in “Model 1”, the foregoing design activities are done by the collaborating partners, while the precast manufacturer is focusing only on the detailed design for the concrete elements, including the reinforcement and installations.

4.3 Analyzing Deviations between Gross Margins and Pre- and Post-calculations

Regardless of the model type, the precast manufacturer and his client typically agree on a contract at a point of time where the preliminary or even conceptual design of a



building is still made. The sales department is using its experience to pre-estimate the amount and type of concrete elements that are needed to construct the designed building. Based on their pre-estimations, the price for delivering the required precast elements is negotiated. Because of the complexity of construction projects [38], estimating the correct sales price is challenging. In case the price is set too high, the precast manufacturer will not be able to compete on the market. On the other hand, if the sales department is offering a too low sales price, the profit will be reduced or the company might even produce with loss. In sum, because at this stage no detailed design information is available, uncertainty and high risk for changes on the design hamper making accurate cost estimations.

Apparently, the sales process in the precast industry is rather complex, as each project requires different products and most of the decisions are made at a point of time, where only little knowledge about the final building design is available and uncertainties about upcoming changes are present. This leads to the obvious assumption that the pre-estimated prices are often not representing the actual costs. In accordance with the developed research question, the results from the qualitative analysis are verified through a quantitative data analysis, leading to the question: how could the company benefit from implementing a configuration system in support of the sales process? By analyzing the current performance quantitatively, the developed assumptions can either be proven or rebutted, so that the highest potential of implementing product configurators would be revealed.

#### 4.4 Identifying the Major Benefits from Using Configuration Systems

To verify the evidence from the qualitative oriented analysis, a nearly complete sample of projects performed over the last 2 years is investigated. Since the objective was to identify how good or bad the accuracy of the cost estimation is, the two proposed indicators from section 3 (depended variables) were set in relation to possible cause (independent variables), e.g. the project size.

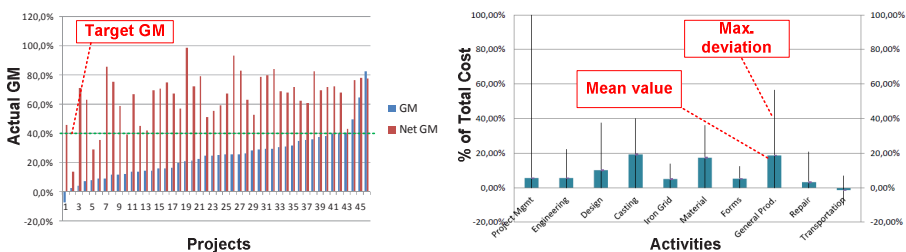


Fig. 4. Deviation between gross margin and pre- and cost calculation

As displayed in Figure 4 above, the projects' GMs and the relative allocation of the costs compared to the total cost were evaluated. To obtain a clear cost picture for each project, only direct and indirect variable costs were considered, leaving out fixed costs, e.g. for administration, and overheads. The graph to the left compares the total

GMs with those when the material costs are excluded (Net GM). The deviation shows that the labor cost do not behave proportional to the project size, as the GM and the one without the material costs do not change correspondingly.

The graph to the right illustrates the strong deviation of the relative activity cost. Here, the pre-work (project management, engineering, design) is not equally distributed across the sizes, but is significantly higher for smaller projects. Also the relative costs for production (casting, reinforcement, forms and material) highly vary with the project size and have the highest percentage for mid-range projects (not in the graph). In sum, the analysis shows a surprisingly high variation of actual GMs and relative cost deviations, where the labor cost is not proportional to the produced elements. Assuming well functioning manufacturing process, the result indicates that the current pre estimation of both sales prices and labor recourses is not being done sufficiently.

## 5 Contribution to Future Specification Process and Cost-Benefit Analysis

When designing the TOBE specification process, the pattern for the deviations has to be revealed. To identify the cause-effect relationship for the strongly varying indicators from the first analysis, the domain experts were asked to provide additional information to the projects and the way they can be compared. Hence, apart from the project sizes, it was decided to consider an estimated complexity factor (based on the produced elements), the model type (see section 4.2) and the project type, e.g. apartments or malls.

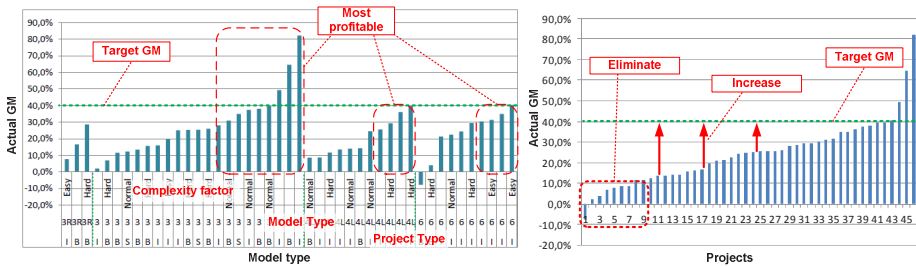


Fig. 5. Analytical results and cost-benefit investigation

The left graph in Figure 5 illustrates the deviation of the GM in relation to the most influencing factor, the model type. The analysis shows that the actual GM is much lower (24%) than the one the company is aiming for. Besides, it becomes clear that the company is most profitable for a certain combination of model type, complexity factor and project type. For these types of projects, the actual GMs were higher and the done pre calculations were more accurate.

Once all influencing factors have been detected, a more precise price calculation model that better reflects the actual cost picture can be designed and incorporated in a

configuration system. The right graph in Figure 5 indicates the scope for decision-making, when deciding on a scenario for the right calculation method. Here, the company has to determine: 1. what would be the minimum GM, which would cover the fixed costs and overheads, and 2. how much could the company benefit from a more accurate price calculation. Indeed, we believe that a sufficient calculation model leads to a stronger negotiating position with the customer and thus helps to increase the GM towards the targeted one. Therefore, more precisely, depending on the company's strategy, we argue that the following possible scenarios shown in Table 2 below might be feasible for the introduced case.

**Table 2.** Cost-benefit analysis

	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
Description	Keep current status		Remove all <10% GM		Remove all <5% GM, increase 5-10% by 5%		Remove all <5% GM, increase 5-10% by 10%		Remove all <5% GM, increase 5-30% by 5%	
Turnover	280		247		275		277		285	
Gross Margin	24%	67	28%	69	26%	72	27%	75	27%	77
Fixed costs and overheads	42		37		41		42		43	
EBIT	28		32		30		33		34	

To ensure anonymity, the total numbers have been changed in the table, whereas their relative ratios have been kept accordingly. A for this industry common EBIT of 10% has been assumed in scenario 1 [36], which further serves as the comparison measurement. Then, in scenario 2 to 5, different combinations of rejected projects with a simultaneous increase of the remaining GMs are proposed. As expected, in the current case, "Scenario 5" appears to be most profitable for the company, where all projects with less than 5% GMs are rejected, but instead the GM for the remaining projects with 5-30% GMs is increased by 5%. However, depending on the market situation, "Scenario 2" or "Scenario 4" might be easier to realize. In these cases, the company would obtain a slightly smaller turnover, but which at the end is overcompensated by the increased GMs and reduced costs, resulting in an increased EBIT.

## 6 Conclusion

The increasing implementation of product configurators over the last two decades has proven a number of potential benefits for companies providing customized goods. However, in academia and practice only little analytical methods have been used to actually uncover these benefits and thus to utilize the maximum capability of the supportive configuration systems. The framework presented in this paper therefore reveals an evident opportunity for better scoping planned configuration projects and thereby to lowering the risk of abandoning projects. To this end, a less discussed investigation of deviations between gross margins and pre- and post-calculations have been applied on an industry case, an ETO manufacturer providing complex building products. The analyses confirmed how a well structured quantified approach, supported by a cost-benefit analysis, can determine the potential advantage of more accurate cost and price calculations and thus lead to improved sale processes.

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## APPENDIX B

# Performance measures for mass customization strategies in an ETO environment

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## Abstract

When following mass customization (MC) principles, manufacturing companies have to consider several aspects. Complexity is thereby seen as a major challenge to be handled. Especially for ETO companies the movement towards MC is much more complex, as products are not standardized, processes are seldom automated and little control over the customer portfolio is obtained. Based on case studies, this research proposes a new way of effectively and efficiently implementing MC strategies. It closely investigates deviations between contribution margins and between pre- and post-calculations of operational measures. The results show the negative impact of high deviations on the corresponding performance.

**Keywords:** Performance Measurement, Complexity Management, Mass Customization

## Introduction

The competitive strategy of mass customization (MC) is recognized as an effective means for manufacturing companies to achieve sustained advantage in a global market competition (Kumar, 1994). It combines the two traditional manufacturing practices of mass production and craft production (Duray, 2002) with the aim to enable companies to provide custom tailored products with nearly mass production efficiency (Tseng and Jiao, 2001). In the last two decades, a vast amount of research has presented the implementation of MC principles (Blecker et al. 2005). Pine (1993) in particular popularized the concept of MC by introducing five fundamental methods concerning the conversion from mass production to MC. Other less common approaches describe how standardization (Kubiak, 1993) and the use of common technology platforms (Pine et al., 2009) facilitated the transformation of engineering oriented manufacturers from an individual customization to a partly MC.

In general, manufactures offering bespoke products which are engineered to the specific requirements of a customer are by definition characterized as engineer-to-order (ETO) companies (Wilkner and Rudberg, 2005). Even though such ETO firms obtain very different characteristics compared to mass producers (Caron and Foire, 1995), their motivation and challenges when perusing MC strategies have seldom been discussed. According to Haug et al. (2009) four principle aspects have thereby to be considered. ETO companies should inter alia focus on reducing the product variety and on creating



an adequate customer variety. Despite the clear formulation, the authors, however, omit to describe how these objectives are to be pursued.

The emphasis of this research is therefore to identify suitable valuation methods which initially assess the current performance of ETO companies moving towards MC. Once successfully completed, such a performance analysis should be capable of specifying how the previously defined objectives towards the implementation of MC strategies are to be achieved. Based on a literature study, first existing concepts and aspects of MC are examined. To evaluate the implementation of MC, additional performance measures are defined. Eventually, a conceptual framework is introduced that strives to better meet the requirements for the intended assessment. The framework is finally tested on three industrial case studies.

### **Research methodology**

A widely used approach for assessing the financial and operational status of a company and monitoring its development over time is to introduce relevant performance measures (Kaydos, 1999). Such measures can be seen as a metric for quantifying the efficiency and effectiveness of an action, where performance measurement describes the process of quantification (Neely et al., 2005). In order to test the analysis method, several case studies of ETO companies are performed. Since full access to detailed data within each company is given, validity of the research findings can be created through an in-depth investigation. To enable a comparison across the studies and thus to achieve external validity (Yin, 2003), each case study preferably follows the same performance measurement approach. Rigor of data collection is insured through foregoing qualitative methods (e.g. unstructured and semi-structured interviews). Subsequently, quantitative data is collected and analysed by means of the proposed methodology.

### **Literature review**

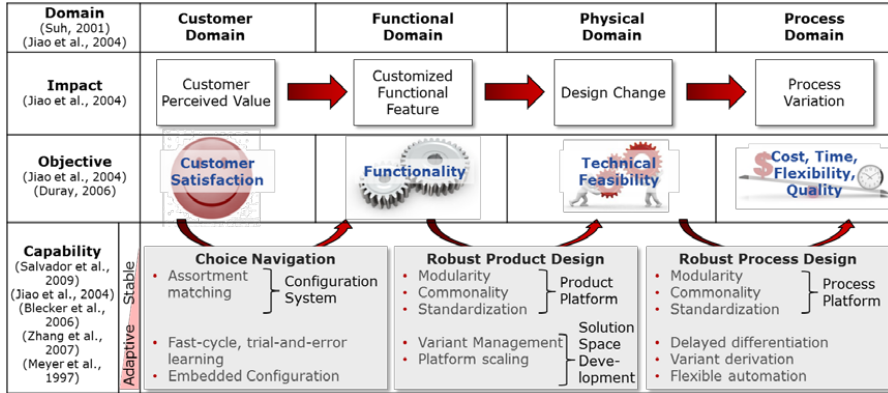
#### *Background and perspectives of mass customization*

Over the past three decades, various strategies and frameworks for defining and characterizing MC have been proposed (Da Silveira et al., 2001). Due to its broad application along the value chain of organizations, literature has been dealing with diverse aspects of the MC concept. While some of the research has been investigating the business and marketing implications of MC, others have examined its impact on operations, product development, manufacturing and supply chain (Fogliatto et al., 2012). For the purpose of this study, we will focus your research on the impact of MC of physical products on the different domains of a company, as proposed by Su (2001), disregarding other areas such as the supply chain coordination, as e.g. discussed by Chandra et al. (2004).

According to Jiao et al. (2004), when customizing products the entire product realization process is affected. As illustrated in Table 1, such a process can e.g. be described based on Su's domain framework (Su, 2001). From the customer domain, customer satisfaction is achieved by a given customer perceived value. This value can be realized by customized functional features in the functional domain, which in turn generate a design change in the physical domain and a variation of processes in the process domain. The objective for the functional domain is to achieve customer satisfaction through a well matching functionality of the product. In the physical domain, technically feasible design solutions are fulfilling the functionality requirements of the requested customization. Eventually, the customized design is realized under the time and cost restrictions of the process domain. Besides, it can be argued that high quality and flexibility should likewise be pursued for efficiently fulfilling of the requested customization within the process domain. After all flexible and reliable processes that quickly adapt to a given

customization order are crucial for the operational performance of mass customizers (Duray, 2006).

*Table 1 - Multiple views of customization*



#### *Generic capabilities of mass customization*

In order to achieve the abovementioned objectives of the domains, researchers have proposed several enablers or capabilities in support of an effective implementation of MC. Based on an extensive literature review, Fogliatto et al. (2012) for example argue, that certain product, process and order elicitation methods and technologies considerably enhance the way how customization is fulfilled within organizations. Their investigation shows that the use of product configuration systems combined with data mining helps to efficiently identify and translate customer requirements into the functionalities of a product. A configuration system is a subtype of knowledge-based expert systems. It represents the product knowledge relevant to the customer (product features) in a formal way, allowing a complete definition of possible product outcomes (customized functional features) with a minimum of entities (Hvam et al., 2011). With the implementation of product platforms, companies can then achieve efficient variety management, as they translate the customized functional features into the design changes (Jiao et al., 2004). Meyer et al. (1997, p. 39) define a product platform as “a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced”. Process platforms on the other hand represent a set of (production) processes that form predefined bill-of-operations and thereby enable the completion of process variations for a given customer order (Jiao et al., 2004). The coordination between the process elements and the ordered product elements can be called variant derivation (Zhang et al., 2007). In order to reduce the complexity caused by the increase of product and process variety, a postponement of the unique variants (delayed differentiation) is desirable (Blecker et al., 2006; Forza et al., 2008).

Similarly, Salvador et al. (2009) propose three general capabilities companies should try to develop when pursuing MC: (1) choice navigation, (2) solution space development and (3) robust process design. With choice navigation a mass customizer should assist customers in identifying their requirements and corresponding solutions (product features) while minimizing complexity and the burden of choice. In the solution space development, a set of functionalities has to be defined which represent best the features requested by a wide range of customers. Eventually, through a robust process design

existing organizational and value-chain resources are reused efficiently under the premise of the process domain, i.e. time, cost, quality and flexibility.

While choice navigation and robust process design can readily be combined with the before mentioned MC methods and technologies, solution space development seems to cover only one of the aspects when linking the functional and the physical domain of organizations. Instead, with respect to robust process design, modelled after Taguchi et al. (2000), we propose the term robust product design, where we integrate the concept of a platform based product development with the described solution space development. In Table 1, an overview of the three capabilities is provided, where we further distinguish between a time-independent (stable) and time-dependent (adaptive) aspects of the corresponding MC strategies. For a comprehensive description of each of the categories, we recommend the related references listed in the table. Companies which manage to transact to a large extend all three capabilities are likely to become successful mass customizers (Salvador et al., 2009).


#### *Complexity and transition characteristics for mass customization*

With the growing intention in implementing MC, manufacturing companies have to accept major changes within their organization. Since customization shapes the entire product realization process (Jiao et al., 2004), many aspects along the value chain of a product realization have to be redefined. However, the transition process towards MC can be carried out effectively, when the undertaken MC strategies are aligned with the aforementioned generic capabilities. Based on a conceptual perspective, Blecker et al. (2006) introduce a logical sequence for implementing a series of MC strategies. The thereby mentioned strategies can be related to development of two of the generic capabilities, namely a robust product and process design. In order to assess the efficiency of the approach, the authors discuss the impact of each of the strategies based on the complexity level companies have to handle, as defined by Su (2005). In result, implementing the right MC strategies should facilitate the handling of an increasing level of complexity. In a related study Blecker et al. (2005) moreover discuss the relationship between the order taking process (assortment matching) of choice navigation and MC, where configuration systems considerably help to handle the increasing configuration and order taking complexity. Even though not further defined by the authors, as illustrated in Table 2, it is reasonable to assume that successfully implemented choice navigation potentially reduces time-independent complexity and indirectly transforms combinatorial into periodic complexity. When implementing configuration systems, customer requirements thus product features are formally described and further mapped with the offered set of functionalities (solution space). Besides, since the provided product variants have to be configurable, first the structural complexity of the product has to be reduced inter alia through the implementation of modular product architectures (Hvam et al., 2011; Orfi et al., 2011). Other business related studies in contrast discuss the impact of complexity on firms' financial performance (Mahler et al., 2009; Kaplan, 2012; Scheiter et al., 2007). Case studies have thereby been used to empirically validate the effect on costs and earnings before interests (EBITs) from restraining the solution space to the most profitable part of the portfolio. However, the relationship to the other capabilities and complexity types has thereby been neglected.

When comparing the transition towards MC from the two extreme cases of manufacturing set-ups, i.e. mass production (MP) and ETO, several major differences can be seen. One main characteristic relates to the customer order decoupling point (CODP), i.e. the point where the in the manufacturing process a product is associated with a customer order (Wikner et al., 2005). Another aspect discussed by Brunoe et al. (2012)

refers to the solution space development. A mass producer typically has a predefined solution space, which due to the increased customization demand has to be gradually extended when moving towards MC. On the other hand, ETO products are engineered, i.e. individually customized, without any predefined limitations with regard to the solution space. Haug et al. (2009) compare those differences according to several aspects, such as product and customer variety, manufacturing and the use of configuration systems. As illustrated in Table 2, when substituting these aspects with the previously defined major capabilities, the mentioned characteristics can unambiguously be related and further aligned with the broader undertaken approach of MC.

*Table 2 - Relationships between capabilities, complexity and characteristics of MC*

MC Capabilities		Complexity Type (Suh, 2005) (Blecker et al., 2006)	Transition Characteristics MP → MC (Haug et al., 2009) ETO → MC	
Choice Navigation			Improve user experience	Reduce complexity of knowledge base
Robust Product Design	Initial		Slight increase of internal variety	Limit internal variety
	Adaptive		Create valuable commercial variety	Create adequate commercial variety
Robust Process Design			Slight increase of cost, lead times & flexibility	Improve processes - cost, lead time & flexibility

## Research objectives

Having theoretically clarified the principal aspects of an effective MC implementation however doesn't necessary explain how the transition should be realized in practice. To be able to provide a meaningful recommendation, further guidance based on real case studies is needed (Fogliatto et al. 2012). Especially from an ETO perspective, literature describing such transition aspects typically concentrates only on one subpart of the three capacities, for instance on how configuration systems could be used in support of the ordering process (Haug et al., 2009; Haug et al., 2011; Brunoe et al., 2012), leaving out any of the remaining transition characteristics unexplained. In contrast, with this study we aim at identifying suitable performance measures which allow an initial assessment of the industrial case at hand and thereby efficiently direct its transition progress towards MC. In particular we investigate what assessment matrix is suitable for the evaluation of a broad range of transition aspects. Thus the research questions to be answered are:

Q1: What are the critical performance indicators that determine the success of a variety of MC strategies?

Q2: What are the limitations of the resulting performance measurement?

Q3: How can possible recommendations for further action be given based on the chosen performance measurement?

## Framework development

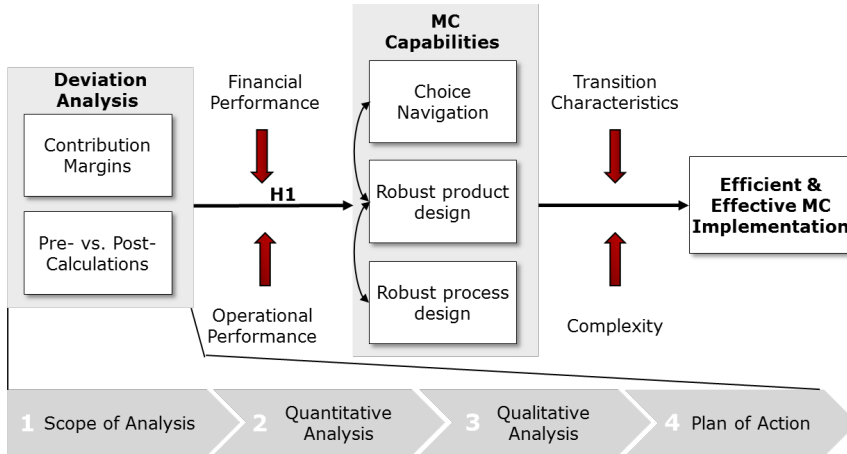
In principle, in order to evaluate how successful ETO firms are with their MC strategies, the various domains of customization have to be investigated (Mortensen et al., 2010). While measuring the operational performance, e.g. cost and lead times, is rather common in the MC domain (Su et al., 2005), the financial impact of customization has less been discussed (Duray, 2006; Forza et al., 2008). Alternatively, including both aspects of operations management (Melnik et al., 2004) into a comprehensive measurement metrics could result in a tremendous task that is impossible to be handled. Since such a metrics could then easily contain an unreasonable large number of key indicators

(Kaydos, 1999), one would easily loose focus on the most critical performance aspects. In a case study, Mortensen et al. (2010) point out that especially manufacturers offering ETO products often struggle with significant contribution margin (CM) deviations. Accordingly a considerable high amount of their portfolio generates no or little profit. Assuming that for similar products relatively stable CMs are pre-estimated, such unexpected deviations may result from poorly made cost pre-calculations. Since pursuing MC requires a clear understanding of the relationships between markets, products and processes, more accurate pre-calculations would lead to better aligned activities. In fact, the comparison of planned vs. realized calculations can accordingly be applied to other operational dimensions, such as time and quality. In result, we propose the following hypothesis:

**Hypothesis 1 (H1).** Investigating deviations between CMs and between pre- and post-calculations of the operational performance reveal potential vulnerabilities of ETO manufacturers moving towards MC, where:

**(H1a)** high deviations between CMs within a product family; and

**(H1b)** high deviations between pre- and post- calculations of the related operations; indicate that MC strategies are not aligned.



*Figure 1 - Conceptual framework for efficient and effective MC implementation*

As illustrated in Figure 1, the conceptual framework underlining the hypothesis links the analysis methods with the discussed capabilities, transition characteristics and complexity aspects for an effective yet efficient MC implementation. The analysis of deviations is suggested to be performed in the following four major phases. As a starting point, in Phase 1 the boundaries for analysis can be set by focussing on a limited number of product families and corresponding projects in defined period of time. In accordance with Mortensen et al. (2010), initially the main characteristics of the product family are categorized from an external perspective, where market segments, customers and key product features are identified. To obtain an overview over the stated project performances, in Phase 2 pre-calculations regarding turnover and the related distribution of costs are collected. Marginal (contribution) costing is then used to provide a more realistic picture about how the turnover is distributed throughout the projects. Since only pre-calculated variable costs are considered, loading incorrect overheads onto products can be avoided (Klook et al., 1997). To achieve further insight, turnover and CMs are

related to the identified market segments, customers, product features (Mortensen et al., 2010; Scheiter et al., 2007). The combination of certain aspects thereby potentially indicates causes-effect relationships of the project success. In addition to cost related measurements, planned lead times, promised quality and desired flexibility of processes can be investigated (Neely et al., 2005). However, as for ETO manufacturers some of the information might not be formally available, in some cases it is useful to first conduct a qualitative assessment of the aspects. Interviews with responsible managers may give indication on what measures to focus on at the first place. Since until then the performance analysis is solely based on the pre-calculated figures, in the following steps post-calculations are applied to validate these results. Activity-based costing (ABC) is used to determine the main cost drivers for each project (Cooper et al., 1991). As most typical activities in manufacturing firms involve by definition manufacturing, sales and procurement processes, for the comparison of the results with the foregoing analysis only labour and material recourses are taken into account. Therefore not directly related resources e.g. for administration are not further considered. In case additional operational measures, e.g. lead times, are found to be critical performance factors, they should as well be included in the post-calculation analysis. By comparing deviations between the planned and realized figures, e.g. promised vs. realized delivery time, additional potential drawbacks can be revealed. At the end of this step, major findings are to be summarized and recommendations for further action are to be set. In order to confirm the results and to achieve data triangulation, a subsequent qualitative analysis (Phase 3) is performed. Interviews with the responsible staff help to identify the rationale behind the results and to either verify or falsify the conclusions. The last step of the analysis (Phase 4) involves a plan of action, where major activities for further action are to be defined according to how successful the capabilities of MC have yet been accomplished.

## **Case description**

### *Data collection and limitations*

To provide empirical evidence for the chosen analysis methods, the proposed conceptual framework was applied on three cases studies. Testing the framework on companies which substantially differ in size, industry and product range helped to better understand it's the practical difficulties limitations. However, it also became more challenging to use a consistent analysis approach throughout the case studies. For instance, while for company A on a high level enough information regarding pre- and post-calculated prices and cost was available, for the remaining case companies big part of the data was not documented. Therefore, for the latter cases already at the beginning of the analysis in Phase 1, additional interviews with managers and engineers from in different department had to be conducted. Especially in case of the pre-calculation related to prices and costs, often much of the information depended on the knowledge of experienced individuals, which was neither documented nor formally described. Therefore, as indicated in results in Table 3, for some measure only qualitative estimations could be obtained. This resulted in pre-calculations which later often turned out be rather unrealistic. On the other hand, a smaller company size proved to be beneficial for investigating post-calculations. Data concerning main cost drivers of projects could easier be investigated, while interviews with the responsible managers helped to identify other operational aspects within the organization. For company A the situation was quite different. Having initially analyzed the project performance on an aggregate level, investigating further details concerning the interesting aspects of the analysis turned out to be surprisingly difficult. Data was mainly available on an aggregate level and in additional, individuals

had a less clear understanding of possible cause-effect relationships with regards to the chosen metric.

Table 3 – Abstract of key figures of the cases companies

	Company	A		B		C	
General	Industry	Oil & Gas		Industrial & Manufacturing Security		Construction	
	Turnover [in Mil. €]/ Employees	6000 / 20.000		100 / 600		50 / 250	
Phase 1	Unit of Analysis	1 Product Family		2 Product Families		Product Portfolio	
	Sample Size	12		550		80	
	Turnover [in k. €]/Project	50.000		20		1000	
Phase 2	Contribution Margin (planned)	Mean: STDEV:	21% 11%	Mean: STDEV:	25% 5% (qual.)	Mean: STDEV:	40% 5% (qual.)
	Contribution Margin (actual)	Mean: STDEV:	8% 18%	Mean: STDEV:	21% 6%	Mean: STDEV:	24,7% 16,5%
	Main Cost Drivers & Deviations	<ul style="list-style-type: none"> <li>- Production (60%±5% )</li> <li>- Engineering (13%±5%)</li> </ul>		<ul style="list-style-type: none"> <li>- Commissioning (20%± 10%)</li> <li>- Project Man. (15%± 10%)</li> </ul>		<ul style="list-style-type: none"> <li>- Production (45% ± 13%)</li> <li>- Material (20±25%)</li> </ul>	
	Main Findings	<ul style="list-style-type: none"> <li>- 50% of the EBIT decrease cannot be explained</li> <li>- Too much resources for repetitive engineering tasks</li> </ul>		<ul style="list-style-type: none"> <li>- High deviation in estimated and actual prices</li> <li>- Unprofitable market segments</li> <li>- High deviation in product quality</li> <li>- Product family inconsistent</li> </ul>		<ul style="list-style-type: none"> <li>- High deviation in project management and engineering</li> <li>- High deviation in estimated and actual prices</li> <li>- High deviation in product quality</li> </ul>	
Phase 3-4	Action Plan	<ul style="list-style-type: none"> <li>- Assortment matching</li> <li>- Product standardization</li> <li>- Process standardization</li> <li>- Variant derivation</li> </ul>		<ul style="list-style-type: none"> <li>- Assortment matching</li> <li>- Solution space development</li> <li>- Process standardization</li> <li>- Variant derivation</li> </ul>		<ul style="list-style-type: none"> <li>- Assortment matching</li> <li>- Flexible automation</li> </ul>	

### Summarizing the results

Table 3 provides an overview of the conducted case studies in relation to the defined phases. Since company A works with relatively large projects that involve the delivery of whole systems, to be able to perform the analysis within the limited timeframe, a rather small sample size was chosen. On the other hand, bigger sample sizes were used for smaller and simpler projects in company B and C. A general outcome of the analysis for all three case studies is that the planned CM performance of the projects was in average overestimated, while the related standard deviation remained continuously on a lower level. Both figures indicate that for a large number of the projects the case companies continuously plan with inaccurate cost estimations, where for extreme cases negative EBITs were achieved. The realized CMs and post-calculations reveal a less stable picture. As expected, the major cost drivers for the projects are costs related to production. Due to the special business of company B, a big cost factor accounts for the commissioning of their products. The main findings from three case studies show that even though the actual performance of their projects was less than what the companies initially expected, the causes can be different. While company A and B have inter alia to put more effort in standardizing their processes, company C appeared to have rather stable process design. However, due to the lack of automation and little understanding of the planned costs, several other drawbacks could be revealed. Company B was advised to redefine on the offered solution space and the target market segments, since in



some cases negative EBITs were unintentionally achieved. Finally, in accordance with literature, all of the three case companies could improve the process of assortment matching through the implementation of a configuration system.

### Conclusion and further work

When following MC principles, manufacturing companies have to consider a number of aspects. The related complexity is thereby seen as a major challenge to be handled (Blecker et al., 2006). Especially for ETO companies the movement towards MC seems to be much more complex compared to mass producers (Haug et al., 2009). Their products typically comprise a low degree of standardization with no or little commonality, their processes are seldom automated and they have little control over their customer portfolio. The presented research aimed at addressing the various domains of MC, complexity and transition characteristics. To avoid the risk of misunderstandings (Piller, 2004), each of the aspect were discussed and set in relation to one another. By considering various strategies of MC, complexity management, as well as current business practices, the study further considered approaches of how to efficiently and yet effectively implement MC. Eventually, a conceptual framework with adapted performance matrices was introduced. To conform to the identified objectives for ETO companies, the suggested approach closely investigated deviations between CMs and between pre- and post-calculations of operational related measures. The results showed how high deviations of the chosen performance measures had a negative impact on companies' performances. Based on the gained findings, recommendations for a further implementation of MC strategies were given. However, since only a limited number of case studies were conducted, in order to obtain a structured guidance for the proposed analysis and to better understand its limitations, further industrial case studies are needed.

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## APPENDIX C

# Knowledge-based geometric modeling in construction

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## Abstract

A wider application of IT-based solutions, such as configuration systems and the implementation of modeling standards, has facilitated the trend to produce mass customized products to support inter alia the specification process of the increasing product variety. However, not all industries have realized the full potential of using product and process modelling tools as well as the implementation of configuration systems to support their business processes. Especially in the building industry, where Engineer-to-Order (ETO) manufacturers provide complex custom tailored products, up to now, often a considerably high amount of their recourses is required for designing and specifying the majority of their product assortment. As design decisions are hereby based on knowledge and experience about behaviour and applicability of construction techniques and materials for a predefined design situation, smart tools need to be developed, to support these activities. In order to achieve a higher degree of design automation, this study proposes a framework for using configuration systems within the CAD environment together with suitable geometric modeling techniques on the example of a Danish manufacturer for precast concrete elements.

**Keywords:** *Knowledge based engineering, geometric modeling, product configuration, construction industry.*

## Introduction

### Background

Unlike most other industries, over the last decades the architectural, engineering and construction (AEC) industry has struggled with achieving any significant productivity improvement [3]. Both, researches and professionals, have therefore been studying ways to gain better performance within this area. Two major approaches have thereby been mainly pursued:

By introducing and adopting lean methodologies to construction, professionals and standardizing associations have initially tried to push forward standardization of products and practices and thereby to reduce waste throughout the construction activities performed by various stakeholders [5, 7]. However, being in a strongly project-oriented business, where each projects is regarded as being unique in terms of design, specifications, context and construction processes [5], the application of formal tools and methods requires comprehensive experience and deep understanding of project specific information [6].

Implementing such a holistic top-down approach turned out to be rather difficult, especially when firms are using separate applications, which are specific for their area of business [7].

More recently, with a wider use of information technologies in the building environment, the industry has then started realising the benefits from transferring the use of IT tools from being dedicated to specific applications, where little or no compatibility was provided, towards more comprehensive solutions [7]. To this end, even though still in its early stage of transformation into a widely accepted practice, building information modelling (BIM) and the creation of common data exchange standards, like Industry Foundation Classes (IFC), have demonstrated a promising potential for an improved way to manage construction projects [8].

### **Research objectives**

Despite all the research effort that has been done especially with regard to the BIM approach, creating tools to support the construction work is still challenging [4]. Tizani and Mawdesley (2011) thus state that in order to facilitate the progress towards higher productivity throughout the building lifecycle, more aspects have to be considered. For instance, apart from the BIM approach, information modeling should also address operational practices of construction. Furthermore, the authors illustrate that with the detailed digital representation of products and processes will help to improve the accuracy and productivity in construction toward a higher degree of automation. Product and processes should thereby follow standardized modeling technologies [2].

Inspired by the industrialization in the plant and machinery industry, with this research we therefore attempt to bring forward the idea of using IT tools and standardized modeling techniques to facilitate a higher degree of automation of the performed construction activities. The focus in particular set on evaluating the current applications of knowledge-based IT support to improve the efficiency of ETO manufacturers in designing geometry-oriented models. A major objective is hereby to automate recurring and non-creative design tasks and to establish generic product models that enable the representation of complex geometry-oriented product architecture.

### **Research methodology**

Based on a literature study, the paper first examines the existing design processes within the building industry and how current procedures of using knowledge-based IT support have thereby been implemented. New methodologies are then introduced that better meet the predefined objectives. To apply the developed methods and techniques, a single case study has been conducted on the example of a Danish prefabricating plant for concrete elements. Being a major producer of precast concrete elements on the Danish market, the studied company has well-established business and production processes and can therefore be seen as a representative example for the precast construction industry. By generalizing the achieved results, the developed methods and techniques can be suggested as a suitable approach for the whole industry.

### **Related work**

#### **Design activities in the precast industry**

Even though building design activities have been performed for hundreds of years, it wasn't until 1960s when the design process was initially formalized [10]. Further descriptions of processes and practices have followed since, aiming to define the activities of the involved stakeholders in detail. The main activities were structured according to the lifecycle of a building, where five major phases were identified: feasibility study, design, construction,

operation and support, and demolition [11]. Going into detail, the design phase thereby contains a conceptual, preliminary and detailed design, clearly separating the design processes from the construction operations [12]. Similar to the design approach in other industries, a preferred design approach in construction is the top-down design [14], where first the overall product, i.e. the building, is defined, followed by breaking it down into subsystems, assemblies and physical components [9]. Based on the initial design intent of the architect, engineers are transferring a design concept into a structural model with the objective to create feasible structural solutions while referring to given architectural patterns and constraints. Such decisions are mostly based on the engineer's knowledge and experience of the realization of the design intents on a given situation [9]. In the detailed design phase further specifications determining the precast elements need to be done to define the structure and assembly layout, the assembly design and analysis and the piece and connection detailing [13]. As most of the building parameters have already been decided, now, concrete calculations of the costs for production can be made. With the focus on specifying the reinforcement, the dimensions and surfaces, and the exact placement of recesses for doors, windows and other installations for each precast element, the design procedure is recurring in nature.

### **Managing knowledge in the design process**

#### *Knowledge-based engineering for repetitive design tasks*

A number of research has been done to investigate how to reduce the resources spent for routine design. Knowledge-Based Engineering (KBE) has thereby been identified as a major approach to study the reuse of product and process knowledge with the aim to reduce the time and cost spent on product development through automation of repetitive design tasks [15]. Depending on the application, various definitions on KBE can be found in literature. Stokes (2001) refers to KBE as "the use of advanced software techniques to capture and re-use product and process knowledge in an integrated way" [16]. According to Chapman and Pinfold (2001), KBE is an "engineering method that represents a merging of object oriented programming (OOP), artificial intelligence (AI) techniques and computer-aided design technologies, giving benefit to customized or variant design automation solutions" [18]. To realize the required integrity, the knowledge to be modeled should therefore be provided within the CAD systems that are used by engineers and architects. Geometrical constraints and heuristic knowledge on the product design can thereby be stored in the so called knowledge base [14]. Sandberg et al. (2011) further state that by using rule-based applications, geometrical models can be represented in a way which is beyond the traditional parametric models. For routine engineering tasks such applications are found being useful [17]. The authors explain how object-oriented KBE software makes use of predefined classes for major geometry objects, such as blocks and cylinders, and predefined functions for modeling parameters, like *min* or *max* functions. Application Programming Interfaces (API) and Macros help to create design and analysis loops, which after a number of iterations can eventually lead to the optimal overall design. As the authors focus on supporting an early stage of the design process, the detailed design is suggested to be carried out in the CAD models, once a suitable product design containing the desired overall parameters has been achieved.

#### *Knowledge-based engineering in construction*

One of the first attempts to implement rule-based design in construction was done by Gross (1996). The author refers to a constraint-based program for developing suitable construction kits. Similar to building up a house out of LEGO blocks, the program defines rules for the dimensions and the positioning of building components, which eventually leads to nearly unlimited possibilities of approved combinations [19]. A similar approach is suggested by

Sandberg et al. (2008), where a configuration system is used to define the dimensions and placement of stairs within a building. The program provides support to the sales and design process by implementing if-then-else rules for choosing the right stair geometry for a given layout and calculating the production costs. To achieve better product documentation and to obtain information on geometry configuration and engineering knowledge, the authors suggest the use of a product data management together with the stair configuration. Even though not further specified, the integration to various CAD systems should be solved through a connection with the API of the systems [20]. A recent study on KBE in the precast industry by Jensen et al. (2012) refers to a rule-based support through the use of a configuration system which is directly integrated into a CAD system. SolidWorks [27] is chosen as a main CAD system for both, making parametric product models and for realizing the communication with product data management (PDM) systems. A standard integration with the configuration system TactonWorks [28] creates the desired design configuration of the dimensions and exports an xml-based parametric file to widely applied architectural CAD software, such as Autodesk Revit [29]. The engineer using this software can then import all precast components and continue the design process manually. Depending on the application area, the communication of the product to the different stakeholders, such as production, engineering and sales, is provided though CAD drawings and lists of rules for dimensioning [21].

The studies described above demonstrate the potential the approach of using KBE in construction has. However, various factors seem to hinder the transformation towards a higher degree of design automation. The first aspect refers to the limited integration and reuse of the product and process knowledge within the CAD system. While in the approaches done by Gross and Sandberg no dynamic integration with the CAD models is proposed, Jensen's study suggests a dynamic integration to only basic parameters of the CAD model, such as the length and width. The suggested consideration of only few main parameters leads to another obvious limitation of the studies. To continue the design process, the obtained product parameters need to be transferred to other CAD systems, where the design detailing of the building components and the corresponding production specifications is performed manually. And finally, even though well defined product information is seen as a key aspect in increasing the productivity in construction [23], none of the studies proposes a suitable technique for making visual the product and process knowledge. Without a clear definition of the product geometry the implementation of variant design automation is done in an unstructured way and thus becomes rather challenging [22].

#### *Geometric modeling for knowledge-based engineering*

As described previously, in order to achieve significant efficiency improvements, more comprehensive configuration solutions that contain detailed design information and which define the parametric boundaries of the product variants need to be developed. Since a higher level of design detail increases the complexity of the product geometry, suitable techniques have to be used to communicate the spatial structure and the corresponding geometric rules of the elements under study. Such a detailed product documentation is in particular needed, when rules, constraints and dependencies have to be defined to be incorporated in the configuration system [22]. The literature dealing with capturing, storing and representing geometrical design knowledge suggests different modeling techniques for describing a product model. Research done within the CAD domain typically tries to use models that are close to the environment of a CAD system. The described modeling methods are therefore mainly based on sketches and on 2D drawings which use predefined notation for symbols, lines, arrows and dots. Together with simple if-then-else expressions, the drawings are used to



express the geometrical constraints and the object behavior of the parametric models [23]. The main purpose of the so called Building Object Behavior (BOB) description is to provide constructability guidance to architects and to reduce the communication cycles with the structural engineers [24]. Therefore, incorporating knowledge of the geometrical constraints directly in a drawing helps to make visual the spatial design intent to architects and technical drawers in an intuitive way. But at the same time it also hampers describing the parametric relations needed for defining the configuration constraints in a formal mathematical way.

A more accepted method for representing geometry-oriented product models, that are to be incorporated in the knowledge base, is the use of class diagrams and generic product trees or Product Variant Masters (PVM) [1, 16, 19, 22, 24, 27-32]. Such a formalized description not only better provides an overview of the product variants and the dependencies of the parameters, but also serves as the basis for the subsequent mathematical formulation of geometric constraints within the API. The examples found in the literature are generally based on established modeling standards for products and processes, such as the Unified Modeling Language (UML) and the Integrated Definition (IDEX) methods. Despite the formalized structure, the used product models reveal some restrictions in providing sufficient information on the design intent and the topology of the product that is to be developed in the CAD system. Even if a defined product model captures all geometric dependencies of an object, it still does not provide any information on how to construct it in the CAD system, what the determining parameters are and accordingly how to define parametric constraints in a structured way. In order to achieve a wider acceptance in the construction industry for using KBE and automating the (detailed) design process, a well defined framework and easy to use tools are needed.

When summarizing the results found in literature dealing with applying KBE and geometric modeling in construction, the following hypotheses on how to achieve higher level of design automation can be proposed:

1. The design knowledge of a product should be dynamically integrated within the CAD system
2. Suitable modeling techniques have to be used for making visual the design intent and the topology of the product
3. The use of KBE should aim to cover a wide range of the design process
4. The design knowledge to be incorporated should obtain a sufficient level of design detail

The following sections deal with the question of how redesign the current way of using KBE within the building industry, while keeping the newly developed hypothesis in mind.

## **The precast industry example**

### **Introducing a procedure for the development of configuration systems**

The use of knowledge-based systems for industrial applications has excessively been discussed in literature [25]. A growing number of cases, where in particular expert systems have been applied successfully, has helped to implement best practices and common concepts. Hvam et al. (2008) present a comprehensive procedure for the development, implementation and maintenance of configuration systems, which are a typical example of expert systems. With this regard, a seven step approach is suggested as a guiding framework for organizations that are dealing with ways on how to implement mass customization, reorganize their way of working and make use of supportive IT tools to streamline their business processes [26]. The industry cases described in this context are typically operating within the electrical,



iLogic [29] is used, the CAD system and the expert system can be realized in a fully integrated way. In case another commercial CAD program and configuration system are chosen, such as SolidWorks and Tacton Works Engineer, the integration between those two systems would be realized slightly different, while the rest of the system architecture would remain the same.

Compared to manually performed design processes, by using the build-in configuration system the work of the designer, i.e. user of the CAD system, could be changed drastically. The designer would be able to use suitable templates, containing information from the knowledge base of a precast element, directly within the already familiar environment of the CAD system. The built-in configuration system iLogic would guide the user through the control parameters via a user interface. Based on his input, the design of the element could be done in an automated way, while a production drawing would be produced of the configured element design and selected parts. This information would then be stored in the Product Data Management (PDM) system and could then be sent further to production. A data manager and a knowledge engineer would maintain the system, as they interpret the design information from PDM system and the restrictions and preferences derived from the production. The created parametric constraints would directly be implemented in the system, by using iLogic's API.

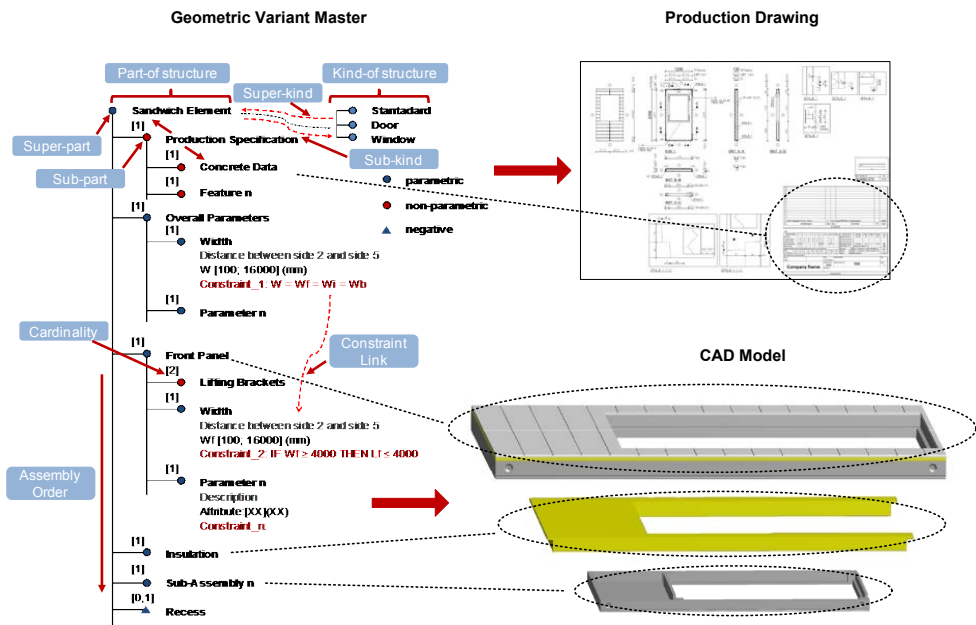


Figure 2 Geometric Variant Master as a Template for the Knowledge Base

In order to record the design information for the knowledge base appropriately, a new way of product documentation is suggested. A so called Geometric Variant Master (GVM) should be used to capture the relevant geometrical knowledge of the product, as well as to communicate the product architecture and the design intent across the organization. The method is based on the well-established product modeling techniques of the PVM [1], where additional notations were defined to better obtain the topology of a CAD model, as well as to include specifications for production. As illustrated in Figure 2, the first part of the GVM specifies the

information, which is needed for producing a concrete element, such as the concrete recipe, the surface quality or the transportation weight. Further down, the assembly order and the topology of the product model is described. The developed notation helps highlighting the occurring parameters that need to be incorporated in the configuration system, including the design restrictions, the parametric constraints and the “negative” parts that are being used to suppress material.

## Conclusion

Even though the use of KBE to support and automate the design process has widely been discussed in academia, analyses show that the current applications of KBE in construction reveal some major limitations, in terms of degree of design automation and design detailing. To overcome these limitations, a framework for using configuration systems, as a widespread example for knowledge bases systems, has been introduced and adopted to the construction business. The introduced methods and techniques have exemplarily been applied on an industry case, an ETO manufacturer of precast concrete elements. The achieved results demonstrate the promising potential of using KBE for geometry oriented models, as the majority of the routine design tasks could be automated and engineering and design recourses could instead be reallocated to the more creative phase of the design activities. However, in order to cover a wider range of the design process, besides focusing on routine design tasks, design automation could be supported by a higher degree of modularization of the building components and their interfaces and by better working data exchange standards.

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## APPENDIX D

# New complex product introduction by means of product configuration

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## Abstract

Configuration systems have widely been applied to efficiently address the customization responsiveness squeeze of companies dealing with Mass Customization. Over time, several frameworks have been introduced to enable their systematic planning, analyses, development and implementation. Traditional research has thereby either focused on defining modelling techniques for the configuration model of stable products, on improved configuration algorithms, or on the impact of configurators on companies' operations. However, little attention has yet been paid how the growing need for product innovation can effectively be supported. Especially for engineering companies moving towards Mass Customization, compared to mass producers the challenges caused by the complexity of their products and by the highly uncertain markets are much higher. This study develops and validates a framework which enables the use of configuration systems along the introduction of complex products. It in particular examines (1) what are suitable development strategies for configuration systems during product innovation, (2) how product development and configuration development can be aligned and managed, and (3) how supplier integration can be achieved.

## 1 Introduction

### 1.1 Background

With mass customization (MC) companies are aiming at effectively addressing the customization-responsiveness squeeze, i.e. the necessity of offering custom tailored products at nearly mass production efficiency [Tseng *et al.*, 2001]. Since its introduction in the late 1980's [Davis, 1989], the concept has received much attention from both practitioners and scientists. General strategies and advanced IT systems, such as configuration systems (CSs), have potentially helped companies to effectively cope with global competition and increased customer demands [Salvador *et al.*, 2009].

### 1.2 Motivation and outline of the paper

While much of the research has yet focused on developing models and theoretical frameworks, little empirical studies have explained the effective introduction of new customized products [Slamanig *et al.*, 2011]. Notably the use of configuration systems has seldom been discussed in the context of radical innovation processes [Hara *et al.*, 2012]. Thus considering the challenges of dynamically changing markets and increasing product complexity [Blecker *et al.*, 2006], further guidance based on empirical evidence is needed. Especially for engineer-to-order (ETO) manufacturers who are moving from an individual customization to a partly MC these challenges are particularly important. Compared to mass producers, their products are typically more complex and high uncertainties of demands make planning activities more difficult [Rahim *et al.*, 2003].

The emphasis of this study is therefore to investigate how new products can be launched effectively in situations in which product complexity (internal complexity) is rather high and where only little information about the customer requirements (external complexity) exists. A particular attention is thereby paid on how CSs can support product innovations for significant product renewals.

Based on a literature study (Section 2), the paper first examines existing approaches for MC with regard to the use of CSs in the context of new product introduction. Relevant frameworks are adapted to better meet the requirements of ETO manufacturers pursuing MC strategies and product innovation with product configuration (Section 3-4). Next, the newly introduced framework is applied on an industrial case study (Section 5), where a configuration model was initially developed. The achieved findings and practical implications are eventually discussed (Section 6).

## 2 Literature Review

### 2.1 Product configuration and mass customization

Offering bespoke products to customers affects the entire product realization process starting from the order acquisition to the order fulfilment [Forza and Salvador, 2002]. According to Jiao and Tseng (2004) the impact of customization can be described with the generic domains of an



organization [Jiao and Tseng, 2004], where to begin with customer satisfaction can be achieved through the efficient match of the requirements to the offered solution space of product variants. Salvador *et al.* (2009) refer to this process as assortment matching, in which suitable software helps to link the existing solution space to customer's needs [Salvador *et al.*, 2009]. The most common software systems that enable the realization of an efficient assortment matching are configuration systems [Forza and Salvador, 2002]. Being a subtype of a knowledge-based expert systems, CSs formally represent the product knowledge relevant to the customer (product features), allowing a complete definition of possible product outcomes (customized functional features) with a minimum of entities [Hvam *et al.*, 2011].

More recently, researches have investigated the use of CSs not only as sales tools, but also in support of the entire specification process, i.e. the order acquisition and order fulfillment process [Forza and Salvador, 2002]. Helo *et al.* (2010) for instance propose a business model for the use of configuration systems throughout the entire specification process of a product [Helo *et al.*, 2010]. The authors discuss how sales configuration can first be used to translate customer needs into functional requirements of a product. In the physical domain, product configuration then matches the chosen set of functionalities into design parameters. Even though not implemented in the study, process configuration can eventually be used to select on a high level suitable production and logistic steps for the subsequent processes. Figure 1 below illustrates a generic value chain of a manufacturing company including its specification process. Depending on the scope of the project, CSs can potentially be implemented to support wholly or only partly the specification process [Hvam *et al.*, 2008].

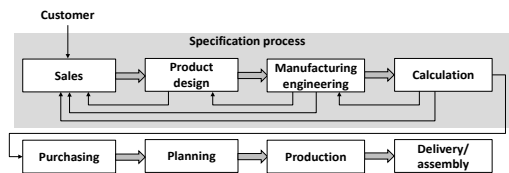


Figure 1: Generic specification process

## 2.2 Recent trends in product innovation

Obviously, by integrating the different customization domains into the configuration process helps to provide salesmen with more accurate estimations of time and cost of existing products. However, over time competition forces firms to update their established product portfolio. Smith *et al.* (2012) discuss two major reasons for companies to regularly work on product innovation:

1. customers change requirements, and
2. product performance needs to be constantly improved [Smith *et al.*, 2012].

Hence, in the first case new products are only introduced when considerable large discrepancy exists between customer needs and the provided functionality of existing prod-

ucts. In the latter case new ideas and technologies keep customers engaged with the products and thus stimulate sales [Howard *et al.*, 2011].

In majority of the cases, working on product innovation is typically based on existing products, where often more than 70% of the development tasks are related to redesigning, improving, and extending the products offered to the market [Ullman, 1997]. To achieve high productivity in the innovation, companies are on the one hand pressured to employ adequate tools and methods that allow an in-depth understanding and managing of knowledge related to products, processes, as well as to their project environment [Vezzetti *et al.*, 2011]. On the other hand, to compete on dynamically changing markets, it has become essential to transform the innovation process from a linear to a spiral model with short and direct iterative loops and feedback cycles [Cooper and Edgett, 2008]. By doing so, initial ideas and prototypes are immediately tested, where early feedback is used for further development [Salvador *et al.*, 2009].

As technology is progressing and being used in more and more areas of business, recent studies demonstrate that a high level of technical assessment in innovation significantly improves companies' business performance. With the use of advanced technologies, probable solutions, risks and potentials can initially be evaluated. Moreover, when considering the costs and benefits from suitable technology in early stages of the innovation process, the need for technology alliances can upfront be detected [Cooper and Edgett, 2008].

## 2.3 Product configuration, innovation and vendor collaboration

Despite configuration systems are playing an essential part in the customization process of manufacturers, in academia their use has typically been limited to streamline specification processes of matured and well established products, usually offered by one vendor [Blecker *et al.*, 2006; Hvam *et al.*, 2008; Forza and Salvador, 2008]. Forza and Salvador (2002) for example discuss the use of a configuration system in support of the order acquisition and fulfillment process of products from one vendor with high but relatively simple product variety [Forza and Salvador, 2002]. Hvam *et al.* (2006) argue for the use of configuration systems as a way to improve the quotation process of ETO products or even systems. By calculating budget quotations, the configuration system manages to create sufficiently precise price estimations offered by one company [Hvam *et al.*, 2006]. Also Haug *et al.* (2012) investigate the use of CSs in several manufacturers of rather complex and engineering intensive products. The authors illustrate the employment of different CS development strategies in support of specifying the existing product portfolios [Haug *et al.*, 2012].

Wang *et al.* (2009) introduce a framework for assessing configuration changes of exiting products. Based on the operational performance of suppliers, a generic algorithm is used to calculate how a changed part affects the preference for individual suppliers. The framework is exemplary tested on a simple electronic device. Even though the authors in-

clude the collaboration of several vendors into their framework, stable products with only minor product changes (different product variants) for relatively simple products have been examined [Wang *et al.*, 2006]. Ardissono *et al.* (2003) propose a theoretical framework for the use of a web-based configuration system which strives to enable the collaboration between different vendors. The authors however omit to explain how the CSs should be used in praxis, especially with regard to complex products and radical innovation [Ardissono *et al.*, 2003].

### 3 Research Design and Objectives

From reviewing the literature it can be stated that none of the mentioned case studies considers how CSs can be used in the cause of innovation and evolvement of a complex product family, in particular not together with the coordination between different suppliers or vendors. At the same time, prevailing on increasingly competitive markets requires efficient innovation processes which are flexible enough to quickly adapt to a fast changing environment [Cooper and Edgett, 2008]. This study therefore aims at developing a framework which addresses the dilemma of being innovative on dynamically changing markets and yet still efficiently providing custom tailored products. In order to achieve practical validity, a case study with a company is performed. The collaboration is organized through action research where the researchers were actively involved in a transformation process [Coughlan and Coughlan, 2004]. The industrial partner is a start-up company, a contractor with a strategic collaboration with several ETO companies.

Already at an early stage of its establishment, the company has realized the potential of using advanced IT technologies and a well thought marketing approach to gain a competitive advantage within its industry. The alliance with the strategic partners enabled sharing the otherwise unreasonable IT investment and the related financial risks. At the same time, such a strong collaboration facilitated the exchange of knowledge concerning the products and potential market segments. Rigor of data was insured through foregoing interviews and through a series of short action research cycles conducted in the cause of twelve months.

### 4 A Procedure for Implementing Complex Product Configuration in NPD

Several frameworks for the development and implementation of CSs exist in literature. For the study at hand, a widely used and well-structured seven phase procedure introduced by Hvam *et al.* (2008) was chosen. The procedure is based on the object oriented project life cycle (analysis, design, implementation and maintenance), and further contains methods for analyzing product ranges as well as the related business processes [Hvam *et al.*, 2008]. Rather than describing each of the phases in detail, in the following, we focus our attention only on the aspects that are critical with respect to innovation and new product development (NPD).

#### 4.1 Clarifying the innovation strategy

By implementing CS several benefits can clearly be gained [Bonev and Hvam, 2012]. Yet, when planning and performing configuration projects with complex products and multiple users, the desired results are often not being achieved. According to Haug *et al.* (2012) a major challenge for the success of a configuration project is that for complex products, the configuration task is difficult to be estimated. In result projects often become significantly more costly than anticipated or companies fail to create prototypes that indicate the potential benefits. Another reason for abandoning initiated configuration projects is that by implementing a CS a substantial part of the business processes have to be redesigned. In case the required organizational changes are not widely accepted by the employees, the system will most likely not be used [Haug *et al.*, 2012]. To overcome these challenges it is important to establish a clear innovation strategy that promotes configuration projects which are likely to succeed and where the risk for failure is kept to a minimum. Thus, to be able to make reasonable decisions about the right innovation strategy it is inevitable to make use of relevant performance metrics. A way of assessing the performance of NPD is through monitoring the NPD productivity measured as the output from the NPD process divided by the input [Cooper and Edgett, 2009]:

$$NPD\ Productivity = \frac{Sales\ (or\ Profit)\ from\ NPD}{R\&D\ Spending}$$

As indicated in Figure 2 below, in today's quick changing business environment the outcome of the NPD can be rather uncertain. Estimations about long term sales development of new products remain vague and can cause high risks with regard to their success on the market [Oriani and Sobrero, 2008].

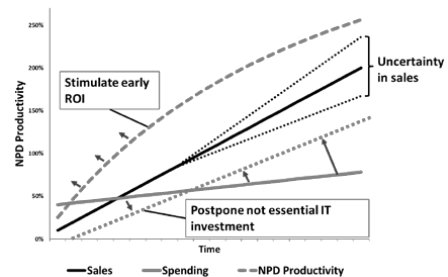


Figure 2: Effect of sales and spending on NPD productivity

In order to increase the NPD productivity and reduce risk of failure in the more reliable planning horizon, i.e. at an early stage of the innovation process, early R&D spending should be kept low. For ETO firms moving towards MC this can be achieved in two major ways. First, it is beneficial to establish strategic alliances with reliable suppliers. By sharing and coordinating innovation activities for complex products and knowledge about customer preferences and trends, individual investments and risks concerning the success on the market can be reduced [Pullen *et al.*, 2012].

Secondly, for configuration projects the R&D spending is mainly driven by the development of the configuration model and by the related IT investment. At an early stage of the configuration project it is therefore important to be clear about what are the essential (“need-to-have”) functionalities the CS needs to have and which of the possible functionalities can be categorized as “nice-to-have”. As the product is maturing over time and turnover from sales is increasing, further investment towards the less prioritized functionalities can be taken and the use of the CS can gradually be extended. From a financial perspective a strategic alliance and a stepwise configuration development stimulates an early return on investment (ROI) and increases the probability for more successful new product launches. Furthermore, a stepwise CS implementation encourages employees to embrace the organizational changes caused by the system, while its functionalities are being extended over time.

In sum, by involving the strategic partners in the configuration project, investment and risks can be shared and a wider range of the specification activities can be considered. Having set the requirements for the innovation strategy, in the following steps the some essential characteristics of the project life cycle will be discussed.

## 4.2 Developing the specification process

Before starting with a detailed analysis on the planned product innovation, if it hasn’t been done yet, it is first useful to establish an overview over the current specification process at hand. From a supply chain perspective it is important to understand how the communication between various stakeholders is organized and to what extent they are influenced by the specification process. A typical sales and delivery process of ETO firms is illustrated in Figure 3 [Brunoe and Nielsen, 2012]. In contrast to mass producers, at the point of sales ETO firms usually have only a limited amount of information specifying the product and a significant amount of it has yet to be designed [Rahim and Baksh, 2003]. At the same time ETO firms still need to be able to create legally binding sales quotes which define the product to a considerable level of detail, ensuring that the communicated price and lead time results in a satisfying profit. Since generating quotations is no guarantee for receiving an order [Kingsman and De Souza, 1997], the sales process has to be effective and very cost efficient. For companies delivering ETO products the main purpose of having a CS is therefore to automate the sales and ordering process [Haug *et al.*, 2009]. In result, this initial analysis of the involved specification activities helps to assess the requirements for the subsequent automation.

Next, a TO-BE specification process supported by a CS can be defined. Scenario 2 in Figure 3 illustrates the most widespread approach for CS [Salvador *et al.*, 2009], namely a sales configurator. In other less common situations, ETO companies might have more benefits from the implementation of a solely technical CS (Scenario 2). In such a case the system would function as a design automation system for generating technical specifications for production. Due to the involvement of complex calculations, a major challenge

is thereby to cover the entire technical specification [Elgh, 2008]. Next, the simultaneous implementation of both, a sales and a technical configurator is repressed by the remaining two scenarios. While in Scenario 3 two separate systems would cover the two aspects, Scenario 4 represents an integrated solution for the configuration. However, as the integration to other IT systems and to advanced calculation and CAD applications, such as to Mathcad and Inventor, is a major cost driver, in the first step this investment it is often unfeasible.

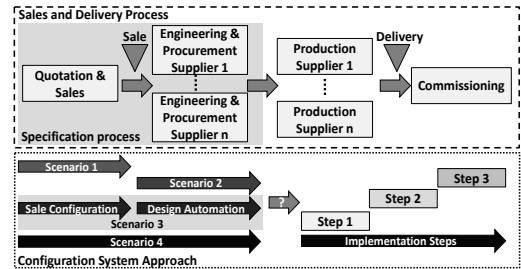


Figure 3: ETO specification and delivery process with a stepwise scenario implementation

Consequently, even though the use of advanced CS can potentially sustain the entire specification process (Scenario 4), to keep the investment costs and the organizational changes at a low level, in the first step (Step 1) of implementation, only the needed process steps are to be assisted by the system. In the subsequent steps (Step 2 etc.), more and more activities related to the specification of a product can be automated. In the majority of the cases it is feasible to start with the development of a sales CS, as for example investigated by Salvador *et al.* (2009). Such a system could then be used as a marketing tool, where in the introduction and growth phase of the product life cycle the focus is on creating customer awareness of the product and on trial of different product variants [Kotler *et al.*, 2012]. With the right analytical capabilities [Davenport and Harris, 2007], companies could quickly uncover customer preferences and thus further extend their product portfolio towards the required product features.

## 4.3 Aligning product analysis and development with configuration development

Since in most cases product innovation builds upon existing products [Smith *et al.*, 2012], after clarifying the implementation steps, an analysis of the most similar product architecture needs to be taken. Ulrich (1995) defines product architecture as: (1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; and (3) the specifications of the interfaces among interacting physical components. For the analysis of the architecture, often the Quality Function Deployment (QFD) and the Design Structure Matrix (DSM) have widely been utilized. With their help customers’ needs are identified and linked into the created product structure [Vezzetti *et al.*,

2011]. The employment of the Modular Function Deployment (MFD) then enables the creation on decoupled functional units, i.e. modules [Ericsson and Erixon, 1999].

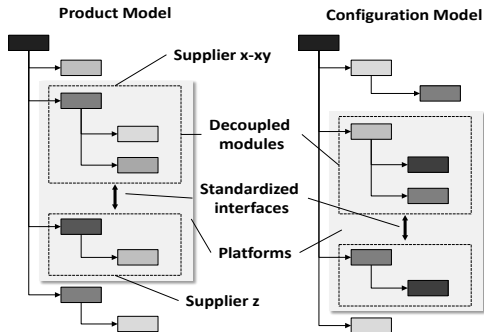


Figure 4: Aligning product model with configuration model

Another way of representing the product architecture is through the hierarchy structure of the Product Variant Master (PVM) technique. By following the basic principles of object oriented modelling, such as generalization, aggregation and association, the PVM technique uses the Unified Modeling Language (UML) standard [Hvam *et al.*, 2008]. Regardless the chosen modeling technique, with product platforms in the development process are more stable product architecture can be achieved [Meyer and Lehnerd, 1997]. To ensure the collaboration between suppliers of a complex product, the individual components should be integrated as separate modules with decoupled functionalities and with clear interfaces to the related product components. Figure 4 illustrates the integration of components coming from different vendors into the entire product model. While some of the modules may be delivered from different suppliers (indicated by “x-xy” in the figure), for other modules only one supplier (“Supplier z”) may exist.

A product model generally aims at representing the physical components and their functionalities. From an object oriented perspective, the development of a configuration model however characterizes the logical combination of classes and their attributes. Each class may represent physical components or other important product characteristics. Such characteristics could e.g. describe geographical, geometrical and functional product aspects, such as the targeted market or the shape and style of a product. Depending on the modelling environment of the CS, as indicated in Figure 4 the configuration model can then be illustrated as a PVM.

Even though the composition of the configuration model might be slightly different from the one of the product model, the same structural concerns are relevant for its knowledge base. Thus, since a growing product complexity typically leads to an increasing configuration complexity, wherever possible the configuration structure should consist of separate configuration modules (classes) with encapsulated constraints [Tiihonen *et al.*, 1996]. To simplify the mod-

el, also here standard interfaces among modules with a minimum number of cross related constraints are beneficial. Classes which can be carried over across product families are then to be grouped to platforms.

Furthermore, in cases where the final product components are unclear yet, a Concurrent Engineering like approach can be achieved by the use of a “black-box” configuration [Whitney, 1988]. In this case configuration classes which contain dummy attributes and constrains for the presumed product functionalities can be established in parallel to the development of the physical product components. Once the final components and the corresponding supplier specifications are available, the placeholders created in the CS can be fed with the actual information. Finally, by using the spiral model [Cooper and Edgett, 2008; Hvam *et al.*, 2008], a quick trial and error testing of the CS helps to detect critical configuration aspects and product components for which the product information is yet fragmented or not available.

## 5 Applying the Framework

The described framework for using CSs in the process of NPD of complex ETO products was tested for validation on an industrial case study. The thereby gained results will in the following be briefly discussed.

### 5.1 Developing the TO-BE specification process at the case company

Having established an overview of the AS-IS specification process, a TO-BE specification process for a stepwise CS implementation was created. The main requirements for Step 1 were:

1. The specification errors, long lead times and limited product representation should be improved by the use of a sales configurator.
2. The sales configurator should:
  - a. Contain only product features which are essential for the customer.
  - b. Store not essential product features as predefined default values and represent for the majority of the cases a well-designed product [Mandl *et al.* 2011].
  - c. Be available locally on salesmen’s computers.
  - d. Provide a sufficiently accurate (95%) price and lead (delivery) time estimation.
  - e. Provide a 3D graphical user interface (GUI) of the product, where a direct impact of the configured commercial features on time and cost is to be seen.
  - f. Generate a quotation for the customer including a description of the configured product.
  - g. Save the customer’s information and the configuration status for a later reconfiguration.

- h. Enable the selection of non-standard choices for better adaptation of the offered solution space.
3. The remaining specification process should be divided into a configurable technical specification process and into a non-configurable engineering and procurement process.
4. The configurable technical specification process should be supported by a technical product configurator, the remaining specifications should be created in a traditional manner (through CAD and advanced calculation systems).
5. Both, the sales and the technical CS should be based on the same configuration model.
6. The output of each of the SCs should work as input for the other SC.
7. The (technical) product configurator should:
  - a. Contain all design specifications of the product which can be configured within the CS.
  - b. Be available on the intranet
  - c. Estimate price and lead times (production, delivery, commissioning) as accurate as possible (ca. 99%).
  - d. Contain only basic descriptions and static pictures of the product.
  - e. Generate technical specifications and manuals for the involved suppliers.
  - f. Save the configuration status for a later reconfiguration.

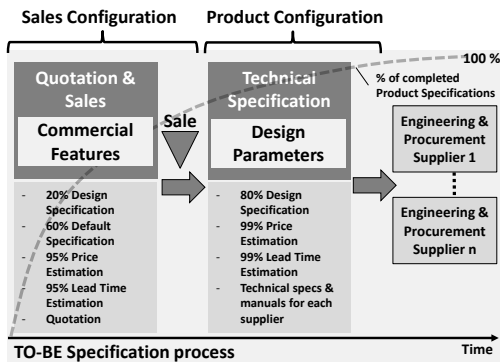


Figure 5: TO-BE Specification process of the case study

Figure 5 shows a high level representation for the chosen initial CS implementation (Step 1). To meet the requirements, a variation of Scenario 3 was selected. For the later steps of implementation (Step 2 etc.), the sales configurator should be available on the internet, where a wider range of customer awareness can be achieved. Another aspect e.g. concerns the functionalities of the technical CS. In later stages the system could have a direct integration to various

CAD and calculation software, so that a higher percentage of the whole product specification can be created. However, since the product consists of components from a number of different suppliers, currently a complete definition of these 3rd party components appears to be unrealistic.

## 5.2 Developing the configuration model at the case company

A generic product model for yet to be developed product family was created by means of the above described modeling techniques. The corresponding configuration model was done directly in the chosen configuration software. Since both, the product and the configuration model were extended over time, the solution space of the models increased dramatically.

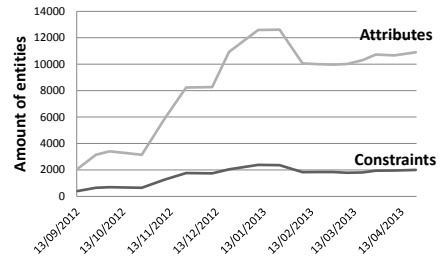


Figure 6: Progress of the configuration model

Figure 6 displays how the number of attributes and constraints of the configuration model grew as it was further completed. The growing complexity of the configuration model led to a higher computation time and to less control over the behaviour and the cause-effect relationships of the system. Hence, several initiatives were taken to reduce the structural complexity of the model. Two of them will in the following be discussed.

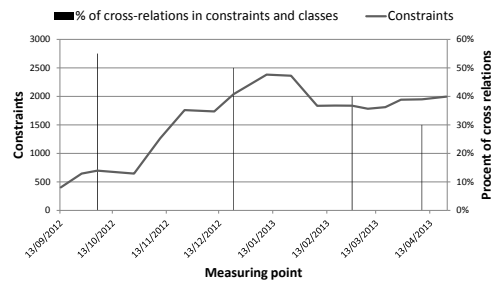


Figure 7: Reduction of cross-relations within the configuration model

To simplify the product structure, first the yet rather integrated construction of the model was redesigned to a more modular form. As described in the framework, wherever possible, it was tried utilize modularization, i.e. to make use of encapsulated classes and thus to reduce the number of cross relations. Figure 7 shows how despite a further extension of the model, a decrease from 55% to 30% cross-

relations in the model considerably reduced the number of needed constraints. Moreover, having encapsulated classes with little cross-relations provided a better overview over the entire configuration model and facilitated the inevitable debugging. In cases of unexpected behaviour, computation or even system errors, the responsible classes could easier be detected.

Solution Space of 4 related attributes for Component A and B		
Category	Solution Space (No. of Combinations)	Structural Complexity
Technically possible	19,360,000,000,000	100%
Simplified each attribute by factor 10	1,936,000,000	0.01%
Simplified each attribute by factor 100 (tolerance limit)	193,600	0.000001%

Table 1: Reduction of unnecessary attribute values

Another way to reduce the complexity of the configuration structure was to minimize ranges of attributes. Since not every technically possible attribute value is required by the customer, the characteristics of each attribute could be reduced to the tolerance limit. Table 8 exemplary depicts how a simplification of 4 attributes exponentially reduces the solution space and hence the structural complexity of the knowledge base. Instead of using the technical possible solution, by limiting the ranges with factor 100 the solution space could be reduced by factor  $10^8$ .

## 6 Conclusion

When following MC principles, manufacturing companies have to consider a number of characteristics. The internal and external complexity is thereby seen as a major challenge to be handled (Blecker et al., 2006). Especially for ETO companies the movement towards MC seems to be much more complex compared to mass producers (Haug et al., 2009). Their products typically comprise a low degree of standardization with no or little commonality, their processes are seldom automated and they have little control over their customer portfolio. Our study shows that in order to better cope with arising challenges, ETO firms need to pay a particular attention on the planning phase of a new product introduction and the related product configuration development. Besides the foregoing product and process analysis (Hvam et al., 2008), several additional aspects need to be considered:

1. ETO companies using product configuration should collaborate on innovation to reduce risk and investment and to become more efficient with the new product launches.
2. Configuration systems should be planned and implemented in steps by using the spiral model, starting only from the most important “need-to-have” functionalities first.
3. Configuration systems should consider the product lifecycle objectives of products, focussing first on the creation of awareness and trial of product variants.
4. Efficiency can be gained in later steps of implementation, as functionalities are being extended, and automation and further integration to other IT systems is realized.

5. The product structure of new products needs to be redesigned in order to be configurable, while 3rd party components should preferably appear as separate modules with standardized interfaces.
6. Product model and configuration model can be created simultaneously, with a focus on stable and well known components. For yet not finally designed components dummy classes with estimated functionalities can be created.
7. In order to handle the complexity of the knowledge base, the configuration model needs to follow the same objectives as the product structure, namely; (a) the use of generic and modular yet encapsulated configuration classes with little cross related constraints (standardized interfaces), (b) the implementation of standardized and decreased attribute ranges.

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## APPENDIX E



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# Scoping a Product Configuration Project for Engineer-to-Order Companies

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## Abstract

*When implementing a product configuration system in a company making complex and highly engineered products, many decisions need to be made in the early phases of the project. This article presents a framework for supporting the initial scoping process and discusses experiences from applying the framework in an engineering company. The framework covers a number of topics, such as identifying the users of the configuration system, prioritizing the user requirements, defining the input and output and considering the overall functionality of the configuration system. Furthermore, the scoping process considers the availability of product knowledge to model into the configuration system, the level of detail and which particular product parts and aspects to include in the system.*

**Key words:** Product configuration, Rational Unified Process (RUP), Scoping.

## 1. INTRODUCTION

Improving the sales and engineering processes with the help of configuration systems is a huge opportunity for enhancing the order acquisition and fulfilment efficiency in companies. Companies offering customized products use product configurators in support of their decision process and to illustrate possible product alternatives [1]. A product configurator is a subtype of software-based expert systems or knowledge-based systems with a focus on creating product and process specifications. It supports the users in specifying a product's different features by confining how predefined entities (physical or non-physical) and their properties (fixed or variable) may be combined [2]. The scope of most of the work done in the configuration conspectus has been very limited and specialized, as stated by Tiihonen [3]. However, in the early phases of a configuration project, decisions are made which are very important for the success of the entire project. At the early phases of a configuration project, it is often difficult to identify and retrieve the right product information to be implemented in the system. Collecting and discussing product knowledge from product experts helps in finding robust modelling solutions, which meet the desired quality. A number of strategies dealing with this challenge have been proposed, such

as the use of a Product Variant Master (PVM) by Hvam et al. [2] and the Product Family Master Plan by Mortensen [4]. Furthermore, in the early phases of the configuration project the scope of products to include needs to be defined as well as objectives and requirements from stakeholders, the IT-architecture, etc.

The present paper focuses the challenge of scoping a product configuration system in companies making complex and highly engineered products. Experiences from projects in this kind of companies reveal that often confusion and lack of focus occur already from the first steps of the project to its final release. This lack of focus often results in both, limiting the performance of the configuration system and increasing the time and resource consumption for developing and implementing the configuration system.

Acting upon this challenge, this paper suggests a framework for scoping the product configuration projects for companies with complex and highly engineered products. This framework is based on a general and well-established framework for scoping IT-systems and on specific methods for modelling a product configuration system.

## 2. LITERATURE BASE

Using a standard framework such as the Rational Unified Process (RUP) as an iterative process helps engineers to perform their tasks professionally in the early phases of an IT project and to develop and test their solutions in short iterations. The RUP methodology includes different tools that empower engineers to learn and work independently. It is a software development process, which contains development techniques and approaches such as object technology and component based development, Unified Modelling Language (UML), architecture modelling, iterative development cycles to verify the model quality, etc.[5]. According to the iterative development principle, the whole system is frequently tested to address the risks of modelling in early stages of configuration projects [6].

In complex and highly engineered products with a high connectivity of components and many constraints, early tests and mistake preventions are vital for keeping development costs at a reasonable level. However, generic development methods, such as the RUP, are not necessarily suitable for every type of project and require content specific adjustments [7]. Jiang et al.(2006) propose a configuration management process model using UML for complex products such as aerospace and automotive industries [8]

### 2.1 Previous research on configuration projects

Configuration systems are essential elements of the information management infrastructure of companies offering a large variety of products, as they enable a number of important product variety management functions [9]. Well running configuration systems can play an important role in enabling these companies to utilise their production capacity effectively and to avoid excessive inventory-holding costs, long lead-times, and high costs [10][11].<sup>1</sup>

The literature suggests that various benefits can be derived from the use of configuration systems. Ladeby and Oddson define the total configuration system (TCS) as a configuration system including the business context in which the configuration system operates [12]. Forza and Salvador define a configuration system as the “set of human and computing resources” needed to “accomplish configuration and modelling processes” [13]. Blecker considered the advisory system as an independent software system. The configurator contains the product model, whereas the advisory system takes over the consulting role [14]. Felfernig, Friedrich, and Jannach (2000) describe representing configuration knowledge with the Unified Modelling Language (UML) in such a way that leads in system development and maintenance [15].

One deficiency common in most of the configuration systems is that they do not completely support stakeholders for the purpose of identifying their requirements [16]. Blecker et al. [14] present a concept of advisory systems for making the interaction processes between customers and configurators simple and short. They discuss the advisory systems technical implementation, and the necessity of their integration with product configurators; and design new advisory systems in a way that they can simplify the process of configuring the products that could provide the stakeholders’ needs [17].

Jinsong, Z. et al. [18] introduce configuration-oriented product model which consists of several sub models: an assembly model, a product function model and a product configuration model. Hong et al. [19] suggest a customer-centric product model called AND-OR trees for determining the relations between stakeholders’ requirements and industrial performance.

Within IT structure main focus in the related articles is on the development of algorithms, methods and tools to solve product configuration tasks covering managing the input/ output and UI structure and the different integration with other systems. Falkner et al. [20] is providing a comprehensive review of these configuration solving approaches. Leitner et al. provide an overview of relevant principles of developing the user interface for configuration environment focusing both on interface for the end users and also knowledge engineers who are in charge of knowledge base development and maintenance [21].

Forza and Salvador discuss scoping of configuration systems focusing on the order decoupling point in the company’s value chain, but they do not discuss which products or which parts of the products to configure. Furthermore they discuss the architecture of the configuration system focusing on technical configuration versus commercial configuration, but they do not include details on e.g. input, output, integrations etc [13].

As illustrated in Table 1, the literature provides input of parts of the scoping, however no scholars have provided a complete framework for how to scope a product configuration system, i.e. identification of stakeholders and their requirements, objectives of the configuration system, the IT-architecture (inputs, outputs, integrations etc.), products and product features to include and a project plan.

<sup>1</sup> The previous literature is identified from researching online libraries by the use of keywords such as “modelling techniques”, “product configuration scoping”, “product configuration”, “IT systems”, “UML” and “RUP”. The references of these papers are reviewed and relevant papers are obtained.

**Table 1.** Approaches to configuration projects

Concepts	1. Aims and purposes of the configuration system: Configuration Systems Benefits	2. Stakeholders' requirements	3. IT structure: Input/ Output Managing and UI	4. Products' features: Level of details updating and maintenance	5. Project plan	RUP
Publication						
Hvam et al., 2008 [2]	X			X		X
Forza et al.[13, 22]			X	X		X
Salvador et al, 2004 [23]	X					
Mortensen et al. 2008 [4]	X	X				X
Haug et al., 2007 [24]			X	X		X
Ladeby et al, 2011 [12]	X					
Blecker et al, 2004 [14]	X					
Tidstam et al, 2010 [25]						X
Jannach et al, 2013 [26]			X	X		
Dviret al, 2003 [27]		X				
Felfernig et al., [1, 15]			X	X		X
Trentin et al, 2012 [28, 29]	X					
Tiihonen et al, 1998[30]			X	X		X
Sabin, D et al(1998), [31]	X		X			
Jinsong, Z. et al. (2005), [18]			X			X

### 3. RESEARCH METHODOLOGY

The purpose of this research is to develop and test a framework for scoping product configuration systems. Based on the literature, we develop a framework for scoping configuration systems by customizing the general framework for scoping IT-systems from the Rational Unified Process (RUP). For this, other theories needed for scoping product configuration systems have been added. These theories are in particular related to the steps of product modelling or functions in a configuration system, aims of product configuration systems etc.; hence, there is a combination of IT project frameworks and product modelling tools. More specifically the framework should include objectives and identification of stakeholders and their requirements for product configuration systems, IT-architecture specifically for the product configuration system, products and product features to be included, and finally conducting a project plan fit for product configuration projects.

### 3.1 Development of the framework

The first phase of the research has been devoted to develop the framework. In this development both related literature study and industrial experiences have been used. More specifically the framework was setup based on general theory on scoping IT systems using UML, tools and theories identified on scoping different parts of product configuration systems; and finally the framework was setup in close dialogue with practitioners and by researchers with a research background in mass customization, product configuration, and modelling products. The authors have been involved in more than 20 product configuration projects in industrial companies, and the framework is also based on experiences from these projects as to which aspects are important to include in the scoping as well as how to apply the scope in the further work on modelling and implementation of the product configuration system.

### 3.2 Test of the framework

For test and analysis of the framework a project team was formed in an industry company, including two researchers from the university, two configuration experts and two IT developers from the case company. The role of the researchers was to provide the framework for scoping the configuration system. The suggested framework was tested and further developed in a close cooperation with the working team in the company. The participation in the testing involved several activities for the researchers, including: describing the steps of the scoping in detail, discussing the scope and optimizing it, and using the scope in the subsequent configuration project. The testing was carried out within a period of 4 months in 2014.

The configuration project selected for the testing parties seen as representative for other configuration projects in companies making complex and highly engineered products.

### 4. FRAMEWORK DEVELOPMENT

Based on the theory presented above, we suggest that a scope for a configuration system should include:

1. Aims and purpose for the configuration system and overall process flow [2, 13]
2. The identification of stakeholders and their requirements [2, 27]
3. IT-architecture incl. flow in the configuration system, UI, input, output, integrations, and the main functionality of the configuration system [2,32]
4. Products and product features to include in the configuration system, incl. level of detail[2]
5. A project plan incl. resources, time table, modelling approach, test and development, system maintenance, etc. [2, 27, 28, 33, 24, 34, 35, 36]

#### 4.1 Aims and purpose of the configurator

This part will discuss the overall aim of implementing the configuration system.

#### 4.1.1 Vision of product configuration projects

The vision states the purpose of implementing a configuration system. What aims should the configuration system follow? As an example, the vision for a specific configuration system could be less time and resources for introducing a new product and fewer errors in the sales and engineering processes. Configuration projects can, in general, be divided into two major categories each having a different vision. The first category is performing sales or the commercial process, and the second one is configuring products for production in the technical process [13].

#### 4.1.2 Objectives and gap analysis

Besides the vision, additional operational objectives can be listed such as [2]:

- Lead time reduction for product quotation and document generation
- Less resource consumption for producing specifications
- Higher quality of specifications
- Quality improvements in quotations
- Higher independency from product experts, etc.

When the objectives of the configuration systems have been formulated, the next step is to carry out a series of measurements in relation to the individual targets. When the targets and the current performance are known, they are summarized via a so-called gap analysis [2]. For example, if the lead time for a current situation is seven days and the target is two days (the aim of the project), this means that a 75% gap or reduction in the lead time is intended.

#### 4.1.3 Process flow

The purpose of this part is to have a standard definition of the current and future flow of business processes.

**AS-IS and TO-BE flow charts:** An AS-IS flowchart shows exactly the current situation of a company and the complications of the process. According to company requirements, there will be a number of scenarios for the future process. TO-BE flowcharts can be drawn according to these scenarios. As an example, the configuration system could have different purposes from varying product perspectives [2] making to order, configuring to order, engineering to order or integrating to order.

### 4.2 Stakeholder requirements

Stakeholder requirements are a wish list from different type of users to be considered in the subsequent steps. One of the reasons for having a strategy in the first phases of a project is to support the prioritization of individual stakeholder requirements. It is important for further development that all stakeholders are identified along with their use patterns. This is necessary in order to prioritize the functions and interfaces of the configuration system [2].

#### 4.2.1 Stakeholder identification

Stakeholders could be among different groups of people such as sales staff, product developers, production staff, marketing staff, etc. with different requirements in terms of the configuration system.

#### 4.2.2 Requirements

These are some examples of stakeholder requirements in different sections: language variety, currency variety, online functionality, required output documents and different user interfaces (UIs). The stakeholders and their necessities can be drawn through two specific methods: the first one is by using process flowcharts (TO-BE process) and the second one is by utilizing the use case diagrams from the RUP method [5]. A use case is a pattern for a limited interaction between a system and actors in the area of application. Use case diagrams are a means of expressing the requirements and the actors involved in the project. According to the RUP rules, the same use case is utilized in system analysis, design, implementation and testing. Note that an actor can be a person or an IT system, which delivers and fetches information from the system. It is vital to develop the system aligned with the user requirements. Thus, it is important to describe the actors and their desired use cases. An actor is a role that includes users or other systems that have the same use patterns [3, 5].

### 4.3 IT-architecture

IT architecture addresses the structure and techniques of a configuration system. As mentioned in the literature part, for the complex and highly engineered products, customers are often overwhelmed by the size and complexity of product assortments resulting from configuration, thus not being able to choose an optimal solution [37] and designing a recommendation system in the IT architecture is recommended. Tiihonen, J et al. [38] discuss how the recommendation technologies can be integrated in the configuration systems to support product configuration and end users. RUP covers almost all aspects of a typical software development project. The IT architecture has to include:

- Definition of the configuration system
  - a) Inputs, outputs
  - b) User Interface (UI)
- Main functionalities such as online and offline functionality
- Decision flow in the configuration system
- Specification of integrations with other systems in the company such as ERP or the calculation systems.

### 4.4 Products and products' features

#### 4.4.1 Which products and which product features to include in the model?

In order to limit the task of registering knowledge during the life cycle of products it is useful to consider the product range from four different points: product structures, product functions and properties, product life cycle properties, variation and family structure [2].

#### 4.4.2 Level of detail to include

Having described which products and product features to include, the next step is to define the level of detail to include in the system. This detail management will help save a lot of time and resources. There are always a number of questions about the level of detail in configuration systems, and it is not easy to answer which aspect of a product should be taken into consideration. If no specific management strategies are used in early phases for controlling details, the impact on the performance and business will be enormous. The technical and business aspects are:

- Further complexity in the configurator
- Difficulties in data documentation, updating and maintenance
- Facing a lack of or additional data when generating documents
- Integration problems
- Difficulties in communicating with domain experts
- Spending a lot of time and resources on gathering irrelevant additional information
- Spending a lot of time and resources on asking questions because of a deficiency of knowledge or due to misunderstandings.

The level of detail is decided upon based on e.g. the needed detail and accuracy of the outputs from the configuration system. Considering lean rules and eliminating waste and non-value adding processes for knowledge acquisition are recommended [39].

### 4.5 Project plan and modelling approaches

#### 4.5.1 An introduction to the Rational Unified Process

The Rational Unified Process(RUP) is a popular iterative and incremental software development process framework. In fact, it is not simply a process, but rather an extensible framework, which should be customized for specific organizations or projects. The RUP is, similarly, a customizable framework. As shown on the time axis in Fig. 1, RUP divides a project into the following four phases: Inception, Elaboration, Construction, and Transition [33].

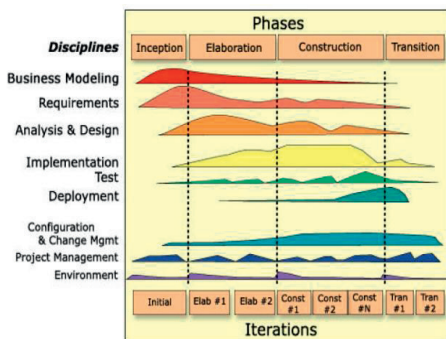


Figure1. Unified Process [36]

The scoping is part of the inception phase, where the modelling approach is outlined, and a project plan is generated. For product configuration, the modelling approaches include methods and strategies such as:

1. Product Variant Master
2. CRC Cards
3. Testing and development
4. Documentation and maintenance
5. Stakeholders' identification with use case diagrams
6. Iteration process for each component
7. Component based development
8. Project planning

"Business modelling" and "requirements" parts in Fig. 1 are purely product configuration modelling techniques, while the rest of them from "analysis and design" to "configuration and change management" steps are related to RUP methods, and project management part is the project planning techniques, containing some tools which are vital for any project. It is also possible to find obstacles for the project in the risk analysis. For a configuration project, a risk could, for example, be complications in the modelling of products or during programming. According to Kruchten many decisions related to an iterative lifecycle are driven by risks, and, for effective decisions, a good understanding of the risks a project faces and, afterwards, clear strategies to deal with them are required [5].

#### 4.5.2 Product Variant Master

The major step is to find the most efficient structured modelling tools, such as the PVM [2]. The purpose is to understand product hierarchy and ensure that all the people in a company have a common view about a product's structure and the variants and constraints.

#### 4.5.3 CRC cards

Detailed information about a product is included in specific cards called CRC cards. CRC stands for "Class, Responsibility and Collaboration", and these cards are used to define classes, including a class's name and its possible place in a hierarchy, together with a date and the name of the person responsible for the class[2]. In addition, the class's task (responsibility), in terms of the class's attributes and methods and with which classes it collaborates (collaboration) is given [40].

#### 4.5.4 Testing and development

Testing is included in the iteration template, and it is as critical for configuration projects as it is for other IT projects. It is seen as an iterative process, which enables early feedback in the early phases of a project. The test work flow will help to measure project quality and defects, and it will remove the need for unnecessary budgeting for debugging processes at the end of a project. Feedbacks from users help to go in the right direction, and users can learn a lot in the early phases of a project. Testing a project step by step makes the debugging procedure easier for both the tester and engineer.

#### 4.5.5 Documentation and maintenance

Documenting the configuration system is the most critical tool for establishing strong communication with domain engineers during and after a project. An efficient documentation system can simplify the communication between the configuration team and domain experts and speed up the flow of gathering, filtering and processing of the information. The suggested documentation system is based on the RUP methodology and modelling strategies, including the Product Variant Master method for modelling product families [2]. Not having a documentation system that supports the modelling techniques means that different software must be applied throughout a project [24]. Avoiding errors and continuously updating the system is crucial for avoiding failure and for getting acceptance of the system. So, expert cooperation with the configuration team will be necessary, especially for highly engineered products. The Agile Unified Process (AUP) developed by Scott Ambler is a simplified version of the Rational Unified Process. An effective agile method in project development, according to Scott Ambler [41], and not keeping information or keeping duplicated information, according to Bran Selic [42], are the most important mentioned points in this research work.

#### 4.5.6 Use case modelling and diagram

Use cases are the means of expressing functional requirements, which are understandable by stakeholders. Use cases create a design model, which can define test cases and plan iterations. Scenarios are the instances of use cases, which are applied for TO-

BE processes in a modelling technique demonstration. Each use case is described in detail, and the use case description shows how the system interacts step by step with the actors. The same use-case model is employed during requirement capture, analysis, design and testing [34].

#### 4.5.7 Iteration process

If a project is too big and has a long schedule, it often seems to have been bound to fail in most companies. Therefore, we have chosen to split this case project into smaller projects. Each phase in the RUP can be further broken down into iterations. Iteration is a complete development loop resulting in a release (internal or external) of an executable product, i.e. a subset of the final product under development, which grows incrementally from iteration to iteration to become the final system [43]. Some benefits from the iteration process in comparison with the waterfall method are: reusing the system, learning during the project and better quality and management. Fig.1 demonstrates the possibility of planning a general iteration loop for configuration projects.

#### 4.5.8 Component-based development

Component-based development is about how to build quality systems that satisfy business needs quickly, preferably by using parts rather than handcrafting every individual element [2]. For a highly engineered and complicated product, the best way is to split it into smaller components and then follow the iteration loop every time and test it. This makes the project less complicated and allows the delivery of the product as soon as possible.

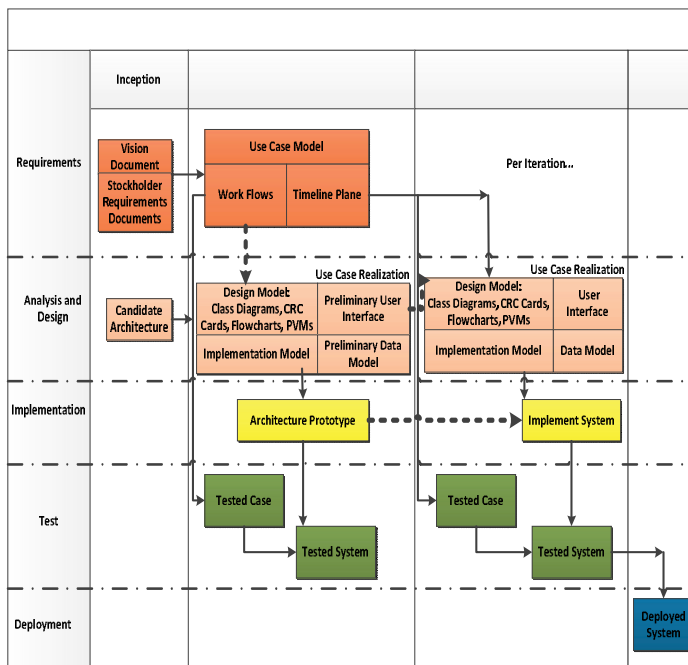


Figure 2. The general iteration process template for configuration systems

#### 4.5.9 Project planning

In general, it is possible to have two different plans. The first plan is a coarse project plan with start and end dates of phases and iterations. The second level of the project plan is a detailed plan for all iterations [33]. Each phase of a project plan should have a specific responsibility. As an example, in the development phase, the following roles could be required: project owner, project manager, facilitator, change manager, end user, model manager, process manager, domain expert and programmer [2]. Every project is a special task, making it difficult or even impossible to plan all the activities at the initial planning phase [43]. Some argue that too much planning can curtail the creativity of project workers [35], and others propose to do milestone planning instead of activity planning. There is no argument about the fact that at least a minimum level of planning is required [27]. In fact, planning is considered a central element of modern project management. There are very important aspects to be manifested in a project plan such as resources for the project and responsibilities, time tables, milestones, proposals, deliverables, success criteria, risk estimation, etc.

### 5. CASE STUDY

The proposed framework has been applied in a real context to assess its functionality. The case company is an international company specialised in the production of heterogeneous catalysts and in the design of process plants based on catalytic processes. The Wet Sulphuric Acid (WSA) process is used in industries like oil refining, coking, coal gasification and viscose fibre use.

#### 5.1 Aims and purpose for the configuration system

A main challenge for the WSA process plant in the case study is within sales and pre-engineering, because a long time (more than one week) was needed to make a quotation. The regional offices all over the world are not capable of making the quotations themselves because of the complexity of the WSA.

##### 5.1.1 Vision

The purpose is to introduce a configuration system, which can act as a knowledge management system, to provide easy access to product information and offer a simple way of making quotations. The system will reduce the lead time for generating quotations for sales people and act as a presale technical configuration system [13].

##### 5.1.2 Objectives

The main purpose of implementing a configuration system is to make the sales process more effective. The system empowers salesmen to act more independently from the technical experts. Hence, in this project, the use of a product configurator will lead to:

- Reduced lead time in sales and engineering processes
- Improved quality of machines and plants
- Increased sales – as it becomes easier to generate quotations
- Reduced complexity of machines and factories
- Cost savings in sales, engineering, production and installation due to the use of product configuration and more well defined and standardised modules in the projects
- Improved accuracy in cost calculations and a decrease in projects that go over budget.

#### 5.1.3 Current situation and future scenario (AS-IS and TO-BE)

In order to describe future scenarios, it is necessary to have a comprehensive overview of the current situation. Sales people are currently using excel sheets and a complex homemade calculation systems as the main foundation for the creation of technical proposals. The calculation system is a way of calculating a complex chemical process. Another problem is that the time spent on generating a quotation is not competitive in comparison to other companies around the world. The purpose of the project is primarily to create a stable tool aimed at generating proposals with as few errors as possible. The accepted scenario is shown in the flowchart in Fig.3 below.

#### 5.2 Stakeholders' identification and requirements

In this case, the stakeholders are sales staff, cost estimators, product developers, marketing staff and regional offices with different requirements to the configuration system. The aim is to find a way to integrate the complicated calculation software into the configuration system and make it easier for sales people to get involved in the calculating process. The overall requirements for the configuration system are:

- Configure a process plant based on feed stream properties and requirements in terms of the emissions of a specific plant type (all stakeholders)
- Combining document snippets into full technical or commercial proposals (sales people and cost estimators)
- Loading technical and commercial data from the configurator into tables (sales, cost estimators and marketing group)
- Price calculation, bills of material and scope of supply (all stakeholders)
- Integration with high performance calculation systems and other systems for receiving the calculated outputs and flow diagrams (all stakeholders)
- A user friendly and independent solution (all stakeholders)
- Currency and language versions (regional offices)
- Online based and saving functionality (sales)
- Easy access to maintenance and updating the system (sales people and product developers).

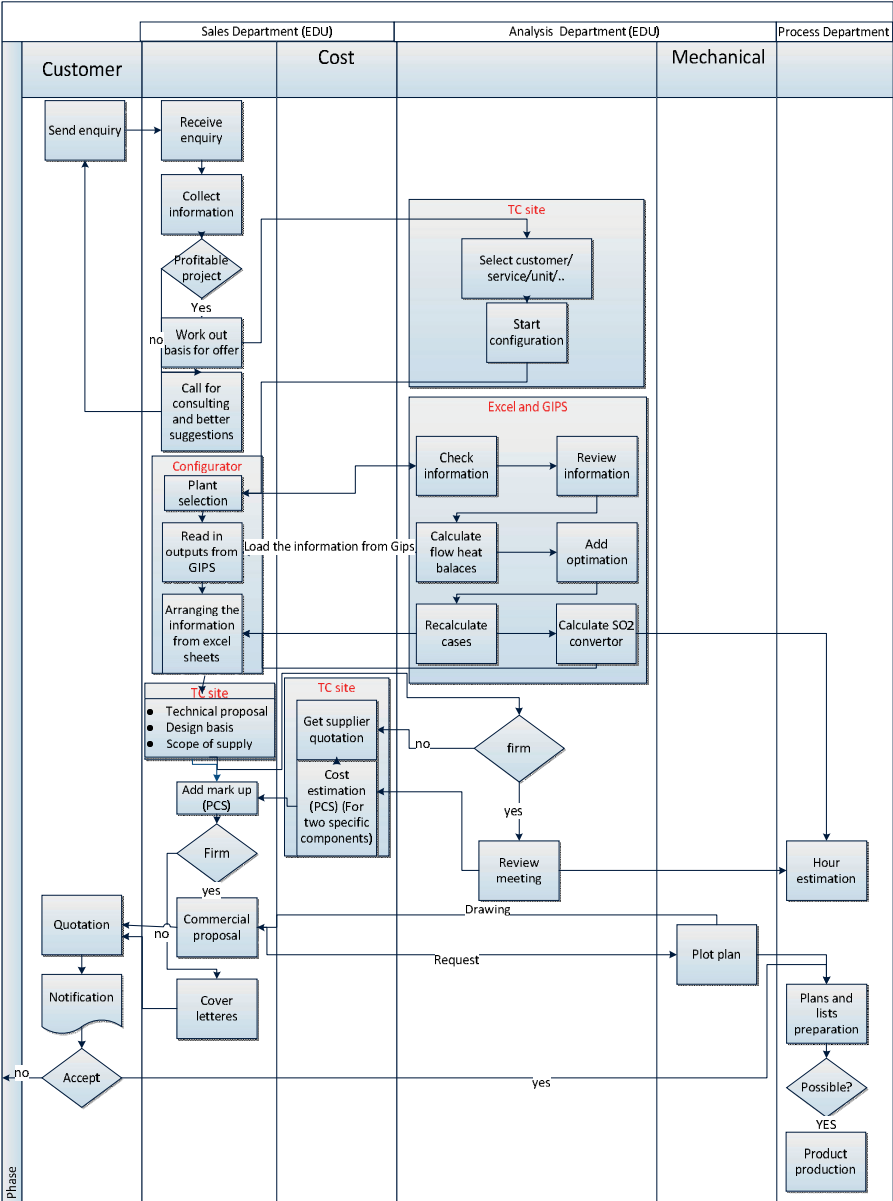


Figure 3. TO-BE process example

5.3 IT-architecture

5.3.1 Inputs/ outputs

Examples of input and output in this case are: the size and volume of the components, the entrance or exhaust pressure and temperature, the number of tubes in a condenser and the number and size of beds in a converter.

5.3.2 Main functionality

Examples of main functions in the configuration system are:

- Capacity dimensioning for the entire plant
- Cost estimation of the machinery
- Needed engineering hours for specification
- Energy consumption during operation.



GIPS CASE 1

GIPS Calculation Number

1100003

(Confirmed)

Start GIPS Calculation

☐ Show GIPS Report

☐ Show GIPS XML input/output

☐ Turbo Calc!

Case Description

(Please Confirm)

Number of Components

4

(Confirmed)

Number of Beds

4

(Confirmed)

Figure 4. The integration user interface example

5.3.3 Integrations

The configuration system used for this case study is a commercial configurator. For each project, much development and much integration are needed according to the stakeholders' requirements. The programmers and developers could perform plug-ins and

integrations according to the stakeholders' request with the desired UI. Fig. 4 illustrates an integration example where a specific plug-in makes tables and draws diagrams according to the tables in the configurator environment. Fig.5 shows the performance of the UI according to the specific requirements.

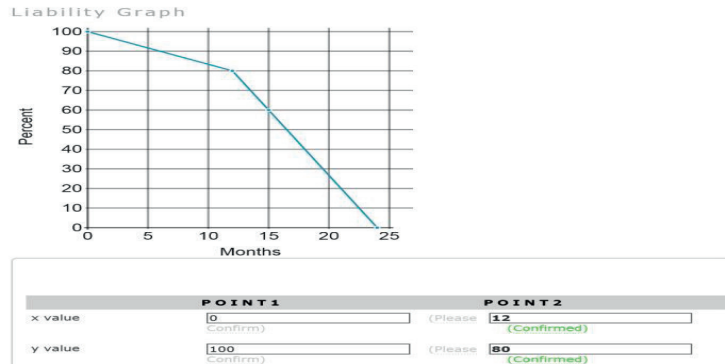


Figure 5. An example for plug-ins in the configurator environment

5.4 Products and product features

5.4.1 Products

WSA plants include several machines and components, which are all engineered-to-order according to customer requirements [2]. Most of them are produced inside the company, and some of them are provided by vendors. The company is covering seven standard plant types, and these different plants vary in terms of their machines and components and the number of machines due on the requested production capacity. There are more than 20 different machines, and some of them are mandatory due to plant type. Depending on the expected catalyst material, others can be optionally selected.

5.4.2 Product features

The product features for the case study focus on property models and product structure models as described by Hvam et al. [2]. The product functions and properties to be modelled are, for example, the price, volume, size and mechanical and chemical properties built into the

property model. The case study is consisting of more than 20 machines, each described with a number of features and constraints. The product structure defines how the products are built up and which parts they consist of. The solution principles in the example include the cooling of machines during the chemical process.

5.4.3 Input/output (level of details)

Fig. 6 gives us a very brief overview of the information needed for our project. The research work for finding a tool to manage the level of detail for input gathering during the first stages of the project is in process. Currently, reverse engineering for finding the outputs' level of detail is being considered. As an example, stakeholders asked for Price Calculation Sheets (PCSs), which are a combination of all component prices according to their internal selections and sizes, the engineering hours based on the plant complexities, consultancy hours, transportation expenses depending on the size and type, insurance

and destination. Taking these requirements for the PCS, it is possible to search for the relevant inputs.

5.5 Project plan and modelling approaches

5.5.1 Product Variant Master

All the discussions about understanding the structure of each individual component have been performed via PVM as a common language between domain experts and the configuration team.

5.5.2 Documentation and maintenance

Concerning the complications in the WSA plants and the importance of updating the engineers in all fields, the set up of a documentation system, was initiated in the early phases of the project. It has been decided to use XML files from the configurator with descriptions to make it possible to transfer all the information inside the configurator with no unnecessary manual intervention. Furthermore, everything inside the configurator, from attributes to rules, will be visible and understandable for everybody in the company and will enable sending comments and updates directly to those responsible.

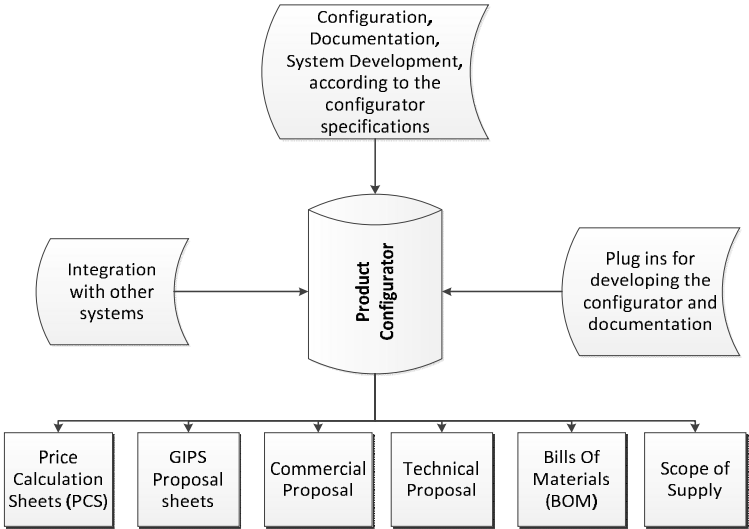


Figure 6. The model subject layer and integration with other systems

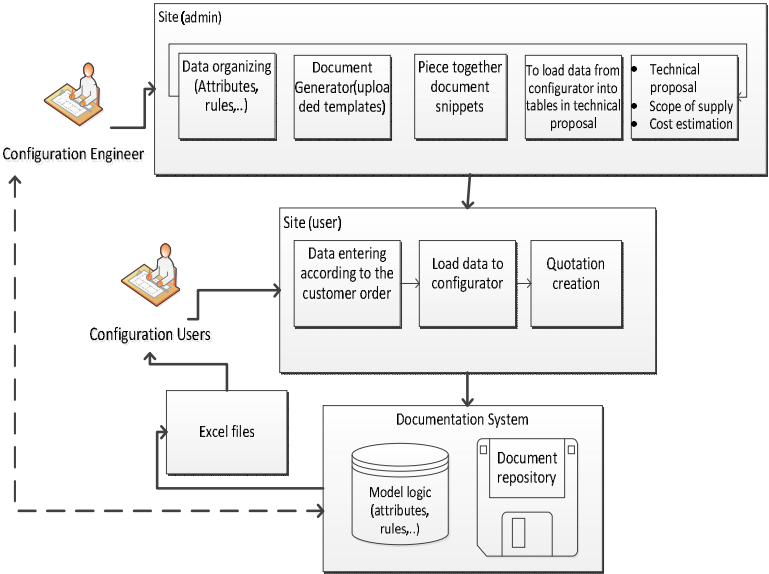


Figure 7. Documentation and maintenance process

### 5.5.3 Use case diagrams for documentation and maintenance

As mentioned, scenarios and flowcharts for the scenarios are a part of the use cases in RUP. In Fig. 7, the use case for the mentioned company has been demonstrated. In fact, specific rules for the use case diagrams should be taken into consideration, as, in RUP use cases are utilized to capture only the functional requirements [5]. Fig. 8 shows the specific use case diagram utilized in the project. However, some use cases, such as integration and documentation, are to be explained in separate use cases as separate sub-projects. In this project, the general iteration process has been used, as described in the previous section.

### 5.5.4 Component-based development

The purpose of using a component based structure is to break a big complicated project into smaller pieces,

making the process easier both for users and developers. When categorizing the expected results and outputs from the configurator, the expectations for the project become more clear. Table 2 depicts the importance of outputs for one specific component (in this case a machine in the process plant) and this way it provides the possibility of comparison and then prioritization in the project. The repeated use of the component (machine) in a factory is considered by multiplying the importance mean value with the number of times the machine is used. In this example in Table 2, the number of this machine in the plant is 2 and it means two of them are necessary for the plant implementation and therefore we need to multiply the importance mean value by 2. As indicated, the configuration project is expected to be challenging as a number of different complex components with varying priorities have to be implemented.

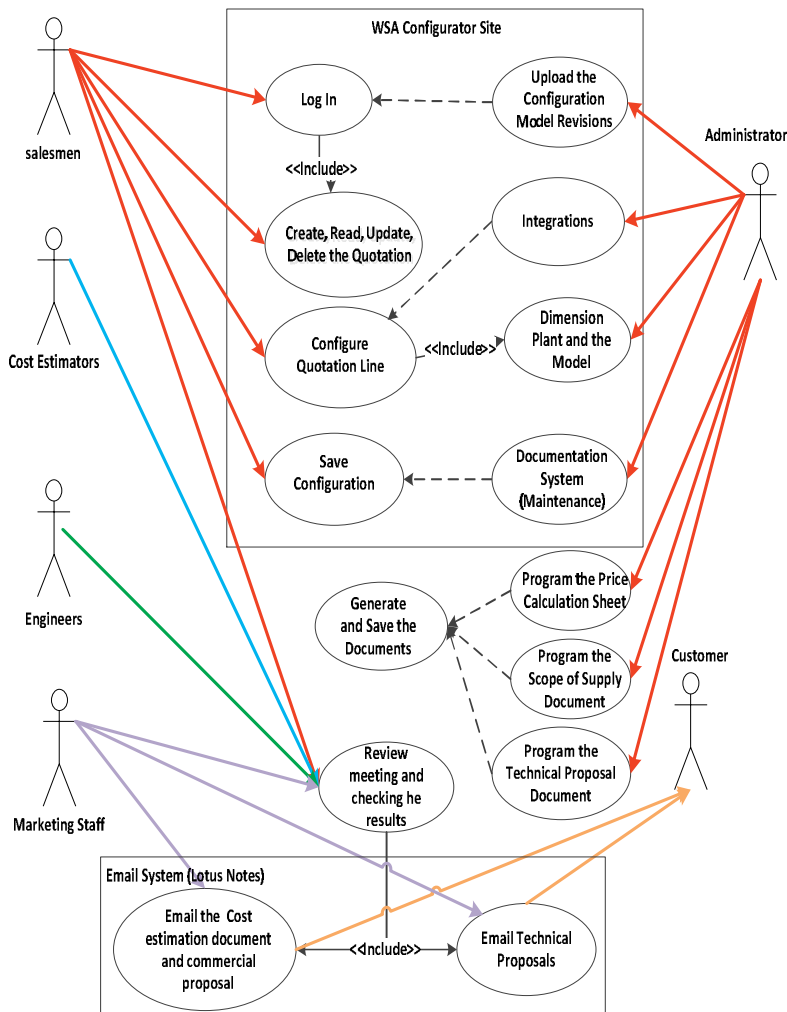


Figure 8. Use case diagram example

**Table 2.** An example for component weighting

Component name	Expected outputs	Importance (0–10)
Condenser	Scope of Supply	9
	Bills of Material	10
	Technical Proposal	5
	Quotations	5
	Hardware lists	8
	Process simulation for integration...	10
Mean value of importance		$(\sum \text{Importance} / \text{No. of Outputs}) = 47/6 = 7.8$

The comparison between the tables related to the components weights is giving a sense of the importance of the components regarding different aspects. This will help the engineer to divide the project and start with the components one by one and combine them all in one project. In this specific case, before any specific plant type for WSA has been selected to be done first; this plant type was the most requested one from the stakeholders and the most sold one in the previous years. Henceforth, the components were evaluated according to their weights and they were divided to three big categories from the first priority components to third priority components and the project was also subdivided to three major versions.

### 5.6 Summary of the case study

In the case company the framework for scoping the configuration system was used in the initial phase of the configuration project. The framework was used a checklist of issues to clarify in the initial phase of the project. By following this “checklist” the configuration team and the stakeholders had a better basis for defining the project and establish a common understanding of the configuration system to be developed from an early point of in the project.

During the project execution the scope developed served as a project definition for the configuration team and as a contract between the configuration team and the stakeholders. During the later phases of the project the initial scope was used and adjusted whenever new requirements arouse from the stakeholders or other changes in the configuration project had to be made.

## 6. DISCUSSION AND CONCLUSION

The suggested framework for scoping product configuration projects is developed based on literature and based experiences from implementing product configuration projects in other ETO companies such as: GE<sup>2</sup>, MAN Diesel and Turbo<sup>3</sup>, APC<sup>4</sup>, FL Smidth<sup>5</sup>, CIMBRIA<sup>6</sup>, NOVENCO<sup>7</sup>, ALTAN<sup>8</sup>, and EMERSON<sup>9</sup>. All these com-

panies are producing complex and highly engineered products like our case study Haldor Topsoe A/S<sup>10</sup>.

These companies are similar from different perspectives. Firstly, they are all producing highly engineered and complex products and they all want to use the product configuration system as a solution for decreasing complexity; and make the sales and engineering processes more efficient [16]. Without a clear scoping from the first stages the configuration system tends to get complicated and with lack of focus. Second similarity is that they are all using the configuration systems for the sales and pre-engineering processes. Thirdly, they work on a high level of abstraction for the configuration projects. The stakeholders for all these companies are highly experienced engineers and sales employees. The configuration system is new to these people, so the configuration team need to discuss the scope with sales people and engineers with no particular knowledge or experience on product configuration systems.

This paper clarifies that having a standard framework for implementing configuration projects has a remarkable effect on decision making in the early phases of a project. The suggested framework for scoping a configuration system has been tested in a case company. In the case company the framework proved to be useful for the project team in supporting an early clarification of the configuration project, and the scope developed formed a solid basis for the subsequent configuration project in that the scope developed helped to focus and give priority only to needed parts of the configuration system. However additional research is required regarding the maintenance and testing stages.

In the case study there were some challenges in identifying and prioritizing the stakeholders and their requirements, which is a field that needs more researches in the future.

Finding a solution for the documentation and maintenance part of the configuration project also need further research. Furthermore, the suggested framework needs to be tested in a number of companies to further validate it, and to test if the framework could be used also in other kind of companies than only ETO companies with complex and highly engineered products.

Customizing the URP methods and combining different modelling tools introduce a scoping framework for the configuration project. This scoping is able to clarify a project plan and the time estimation for the project managers and configuration team even before project

<sup>2</sup><http://www.gea.com/en/index.html>

<sup>3</sup><http://dieselturbo.man.eu/>

<sup>4</sup><http://www.apc.com/company/dk/da/>

<sup>5</sup><http://www.flsmidth.com/>

<sup>6</sup><http://www.cimbria.com/>

<sup>7</sup><http://www.novencogroup.com/>

<sup>8</sup><http://altan.dk/>

<sup>9</sup><http://www.emerson.com/en-US/Pages/Default.aspx>

<sup>10</sup><http://www.topsoe.com/>

commencement. The case study indicates that having a framework for scoping including e.g. determining stakeholders' requirements, modelling tools, management of input and output, levels of controlled details, maintenance and documentation is a valuable means for defining and controlling configuration projects.

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# Određivanje okvira projekta konfigurisanja proizvoda u preduzećima koja se bave inženjeringom prema narudžbini

Sara Shafiee, Lars Hvam, Martin Bonev

Primljen (12.07.2014.); Recenziran (02.11.2014.); Prihvaćen (02.12.2014.)

## Rezime

*Prilikom primene sistema za konfiguraciju proizvoda u preduzeću koje proizvodi kompleksne i sofisticirane inženjerske proizvode, mnoge odluke je potrebno doneti u ranim fazama projekta. Ovaj članak predstavlja podlogu za podršku inicijalnom procesu određivanja okvira i diskutuje iskustva iz primene okvira u inženjerskom preduzeću. Okvir pokriva više tema, kao što je identifikacija korisnika konfiguracionog sistema, određivanje prioriteta u zahtevima kupaca, definisanje ulaza i izlaza i razmatranje sveukupne funkcionalnosti konfiguracionog sistema. Nadalje, proces određivanja okvira razmatra raspoloživost znanja o proizvodu koje je potrebno modelovati u konfiguracioni sistem, nivo detalja i koje delove proizvoda i aspekte je potrebno uključiti u sistem.*

**Ključne reči:** konfigurisanje proizvoda, racionalni iskustveni pristup, određivanje okvira.

## APPENDIX F

# The Use of Modelling Methods for Product Configuration in Industrial Applications

Lars Hvam, Martin Bonev, Anders Haug  
and Niels Henrik Mortensen

**Abstract** Developing product configuration system (CS) requires extracting and representing domain expert knowledge in appropriate product models. As acknowledged by researchers, this is often one of the most challenging activities in configuration projects, where only little empirical insights have yet been reported. This article investigates the challenge on how industrial companies model their product CSs. The study is based on interviews of 18 industrial companies using CSs for configuring customer-tailored products. It investigates the relationship between using a structured modelling technique for modelling product families relative to less or no formal approaches. Furthermore, the study explores the specific characteristics of configuration set-ups with respect to size and complexity and their effect on product variant management and availability of product knowledge in organizations. The results empirically validate the need for a suggested systematic modelling approach for large and complex configuration projects and its positive effect on the overall performance of companies.

**Keywords** Mass customization · Product modelling · Product configuration · Object-oriented modelling

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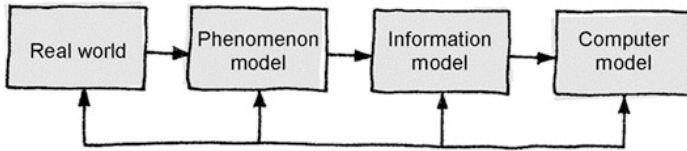
## 1 Introduction

With product configuration systems (CSs), companies can obtain the growing product variety caused by today's global market competition in an efficient way [1, 2]. They represent one of the most successful applications of artificial intelligence principles [3–5]. A product CS is a software-based expert system that supports the users in the specification of customized products [6]. The system provides design choices for the user, while restricting the offered solution space to feasible combination of choices. Having a predefined knowledge base, CSs enable automating repetitive product specification tasks, for which human experts were previously needed. Their implementation has resulted in a number of operational benefits: such as reduced lead times, better quality of specifications, improved on-time delivery and less training for new employees [7–9]. In many cases, product CSs have been used to create quote prices, sales prices, bill of materials, and other product specifications. They incorporate knowledge-integrated or intelligent models of the product portfolio. Based on these models, new specifications for product instances and their life cycle properties can be derived. The development of CSs requires that domain expert knowledge is extracted and represented in corresponding product models to be incorporated in a CS. As acknowledged by researchers, this is often one of the most challenging activities in configuration projects [1, 4, 10]. However, only little empirical studies investigate the character of the modelling methods applied in industry and their usefulness with regard to nature of the configuration project. Instead, academia typically focusses on proposing various modelling methods based on conceptual examples or single case studies, e.g. [11–14]. To better understand this relation, this article evaluates the experiences from applying a structured approach for modelling product variants for product CS in relation to less formal methods. The implementation of a comparison framework for such a systematic approach is examined relative to less formal modelling techniques, e.g. structured bills of materials, or to no specific methods at all. The qualities of the suggested modelling procedure are yet not compared to other related modelling techniques.

## 2 Literature Review

### 2.1 *From Real World to an IT-System*

The development of a computer model can be expressed in several phases. Figure 1 shows the so-called phenomenon model and the information model as means for modelling real world objects for an IT-system. In the context of product CSs, such a transformation represents modelling product variants for a product CS. Based on the actual product family and its variants offered on the market, a phenomenon model is



**Fig. 1** From real world to an IT-system (adapted from [15])

developed and further formalized into an information model—an object-oriented model, which facilitates the transformation into an IT-system. Finally, the information model is implemented into a computer model, for which the same features and constraints are used, changed and updated across the phenomenon model, the information model and the computer model [15].

The challenge of modelling product knowledge has been discussed by several authors and alternative representation techniques have been suggested [1]. In the majority of cases, the proposed methods make use of the unified modelling language (UML) standard for the representation of the product knowledge and in particular of the information model [8]. Aldanondo et al. [11] for example introduce a combination of class diagrams, constraints expressed with natural language, as well as a number of inter- and intra-domain matrixes depicting the relationship between product components, operations or attributes. Chao and Chen [12] propose the use of a “general design” model, which expresses the relationship between components and assesses their ability for a physical assembly before production. Even though not discussed by the authors, the model makes partly use of the UML standard, e.g. to describe decomposition or cardinality. Also Magro and Torasso [16] investigate the possibility of providing a sufficient model for the representation of the product knowledge. The authors suggest a frames parts components (FPC) model, as a means of describing the relevant product knowledge. The mentioned technique can be seen as a modified UML model with a reduced syntax for the expression of, e.g. aggregation and generalization structures. Through its simplification, the authors argue for its visual support of sequential configuration algorithm examples. However, it remains unclear why the given and more comprehensive UML standard would not be at least just as suitable for the discussed configuration problems. Alternative methods have, e.g. proposed the use of feature or functional hierarchy trees [13, 17]. Based on such an initial meta-modelling of product functions, a more detailed configuration model is then acquired with class diagrams using the UML standard.

## ***2.2 The Centre for Product Modelling Procedure***

A more comprehensive approach has been taken by Hvam et al. [1]. The authors suggest a set of modelling techniques for modelling product families for product configuration [1]. The so-called Centre for Product Modelling (CPM) approach

focuses on the phenomenon model and its transformation into an information model. The CPM procedure includes the use of a generic product variant model, the so-called product variant master (PVM) and class responsibility collaboration (CRC) cards for modelling product families. Here, a product model can be defined as a model that describes a product's structure, function and other product's life cycle properties, e.g. manufacturing, assembly, transportation and service [18, 19]. As it includes a definition of the rules for generating variants in the product assortment, it is used as a basis for a product CSs [1, 20]. However, experiences from a considerable number of industrial companies have shown that often these product CSs are constructed without the use of a strict modelling technique. As a result, many of the systems are unstructured and undocumented and therefore difficult or impossible to maintain or develop further [1].

In order to cope with these challenges, according to theory, the introduced method makes it possible to document the product CSs in a structured way. Furthermore, the modelling techniques enable to involve domain experts from, e.g. sales, product development and production in the modelling process. This improves the ability to make the right decisions on which products and features to include in the CS. Consequently, a stronger commitment behind the product knowledge implemented in the CS can be achieved.

The main principles of the PVM technique can be seen in Fig. 2. The left-hand side of the model contains the generic part of structure, also known as the aggregation structure from object-oriented modelling. The generalization which describes how a product part can appear in several variants, the so-called kind-of structure, is listed on the right-hand side of the model. In the PVM, a description is also given of the most important connections between modules/parts, i.e. rules for which modules/parts are permitted to be combined. This is done by drawing a line between the two modules/parts and writing the rules which apply for combining the modules/parts concerned. In a similar manner, the life cycle systems to be modelled are described in terms of masters that for example describe the production system or the assembly system. The individual modules/parts in the PVM are further described in CRC cards, which are used to detail the individual object classes [1, 19, 21]. They moreover contain information about product responsibility, version control or sketches and can be associated with both the PVM and the object-oriented analysis (OOA) model. The purpose of the CRC cards is to document detailed knowledge about attributes and methods for the individual object classes and to describe the classes' mutual relationships. The CRC cards serve as documentation for both domain experts and system developers, and thus, together with the PVM and the class diagram, become an important means of communicating and documenting knowledge within the project group. With their creation, a class diagram as an object-oriented model based on the UML standard can then be developed. Due to its systematic framework and the relative frequent use, the hereby described approach is further taken as a comparison model for a generally structured modelling procedure for CSs.

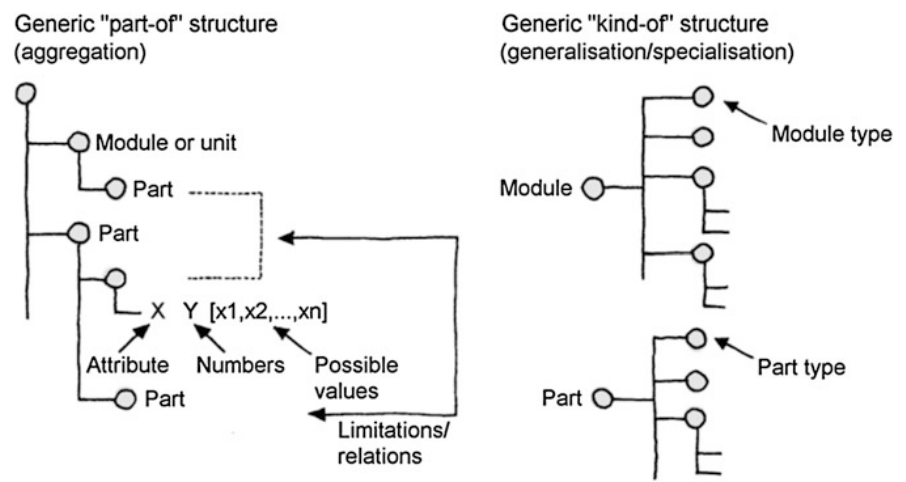
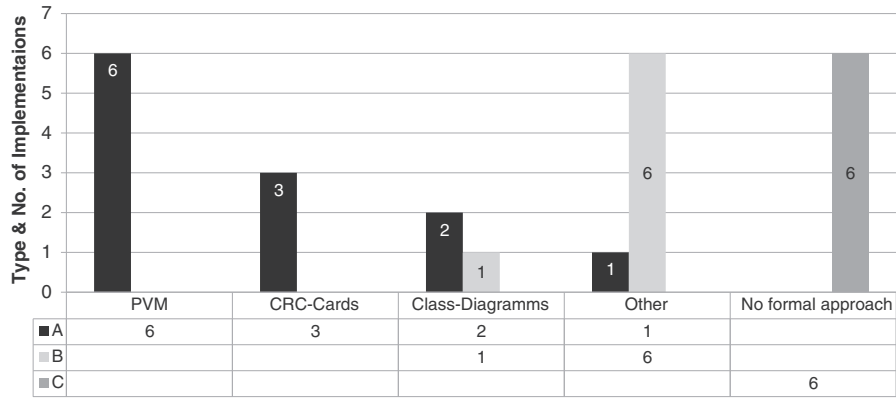


Fig. 2 Principles of the product variant master (taken from [1])

3 Research Method

To investigate the actual use of modelling techniques in product configuration projects, an investigation on the use of product CSs in industry companies was carried out. The study was conducted as semi-structured interviews of employees with knowledge of the configuration projects. The main reason for using interviews instead of a web-based or paper-based questionnaire survey is that the area in focus is characterized by a much unclear terminology. The chosen approach allowed for the interviewer to clarify the meaning of questions that are not understood and to rigorously investigate the nature of the configuration set-up. This option proved to be particularly helpful because of the different backgrounds of interviewees and the different industrial settings, definitions and practices of the target organizations. Furthermore, the research design made it possible to balance the breadth and the depth of the case studies by allowing for both qualitative explanations and quantitative indications.

A total of 26 companies were interviewed for the study, where a sample of 18 companies was selected based on: (1) the interviewed being able to explain the modelling techniques used and (2) the interviewed being able to state the effects from using product configuration. All 18 case companies offer business-to-business products, where in ten of them, several CS are in operation. The evaluation of the interviews enabled a general classification of the 18 companies with regards the modelling approach in three different categories, with six in each category. Figure 3 illustrates the modelling distribution for each of the categories. All companies belonging to category A were using the suggested PVM technique, three were using CRC cards and two companies also used class diagrams. Companies belonging to category B reported using structured bills of materials as their dominant way for



**Fig. 3** Applied modelling techniques per category

defining the variants in the product families. Besides, they apply Excel spread sheets, Word documents and the modelling environment provided in the product configuration software. The remaining C companies claimed not to use any specific modelling techniques outside the configuration tool, except of product tables in Excel spread sheets and specification reports in Word documents. The results of the configuration set-up in relation to the used modelling approach are discussed in the following section.

4 Results

4.1 Effects of the Configuration Set-Up on Company Size and Market

Figure 4 provides background information on the investigated companies and the size and purpose of their CSs. As indicated in Fig. 4, CSs are used across all three categories in support of the quotation and production process. More precisely, 17 out of 18 of the companies apply product CSs for quotations. Sixteen of these use the product CSs both for creating quotations and for the manufacturing specifications, while only one company uses product CSs solely for creating manufacturing specifications. In most cases, such product CSs were created by using the same standard configuration software shells. In the context of counting the number of product CSs, a single product CS is defined as being each running software application, which has an individual knowledge base.

Companies belonging to category A are typically globally operating firms, which are larger in average (84 % bigger than the mean value) and have a high share of customized products compared to configured ones. They are mainly offering industrial systems, plants and machineries, which require a strong engineering

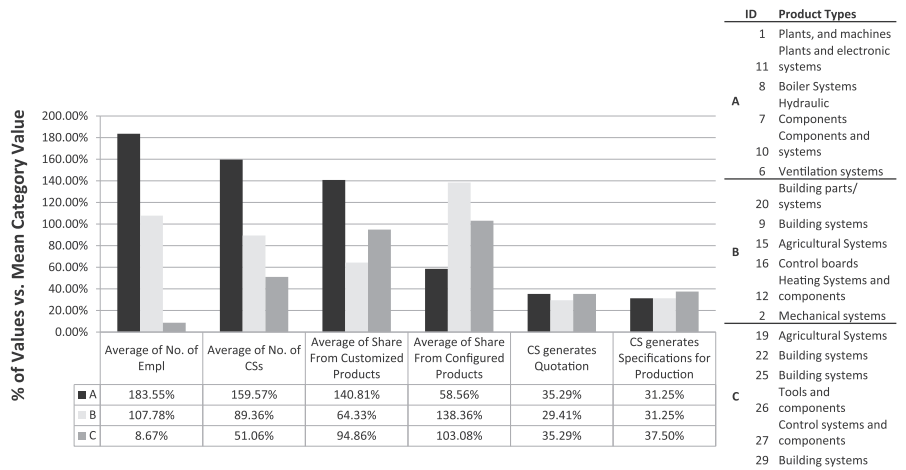


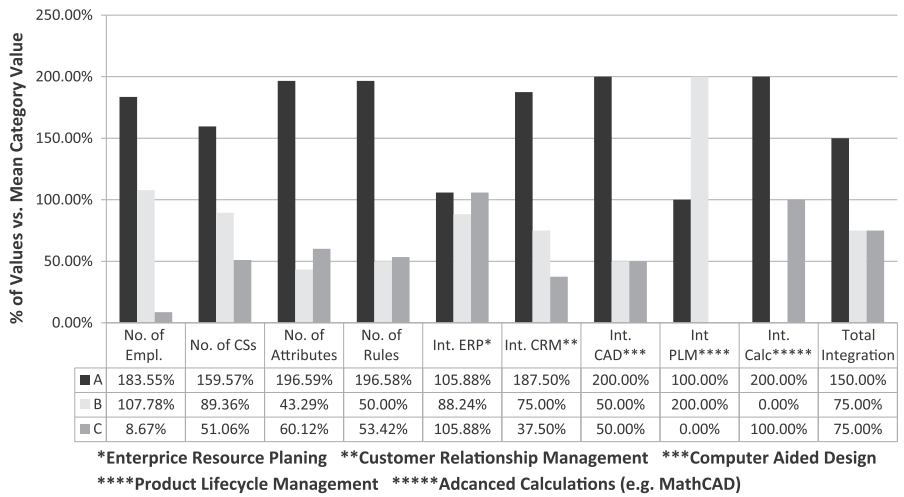
Fig. 4 Background information and configuration support

effort. To support the customization of their complex products, they have implemented several CSs (60 % more than the mean value). This helps them to configure ca. 30 % of their product range, while remaining part of their portfolio today involves additional engineering workload.

Compared to A firms, companies belonging to category B are in average smaller in size, yet globally operating. They are producing building, agricultural and mechanical systems and use a limited number of CSs for a large part of their product range. Next, C companies are considerably smaller in size. They are typically locally operating firms working within building and tooling sector, where ca. half of their products are supported by generally one CS.

4.2 Effects of the Configuration Set-Up and Complexity on the Modelling Approach

When investigating the detailed set-up of the individual CSs in the case companies, a major difference can be revealed. Companies in category A use several CSs for relatively complex products and with a strong integration to other IT systems (50 % more than the mean value), such as CAD or ERP. In order to handle the configuration tasks, each of their CSs comprise a large number of attributes and rules. Due to the increase challenges in modelling their product portfolio for configuration, all of the A companies were using the suggested CPM modelling techniques. But as the CSs grew bigger and the number of people involved in the configuration projects increased, they realized a need for being able to work in a more structured way and for being in more control of the models implemented in the product CSs. Here, three of the six companies using the CPM procedure have



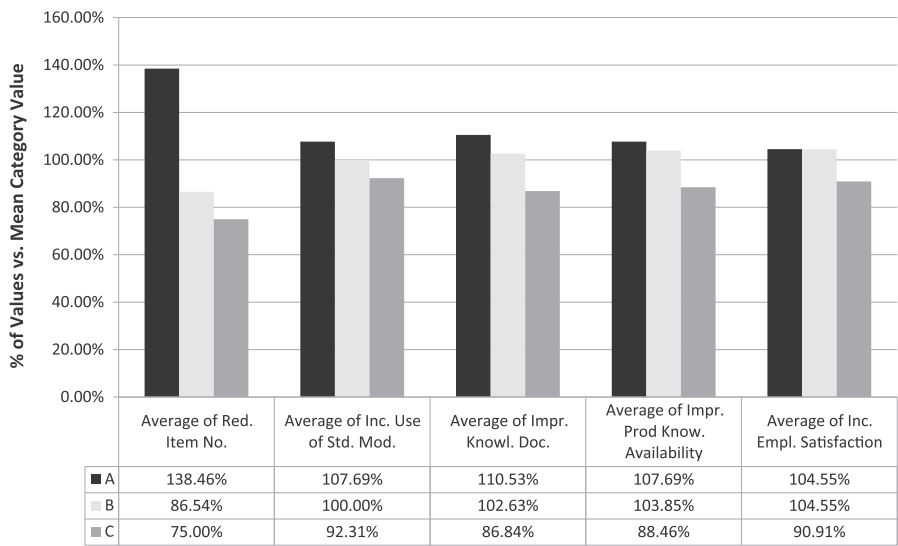
**Fig. 5** Effects of product configuration complexity on system integrations

reported that they started to model their product CSs without any specific modelling technique.

As Fig. 5 reveals, companies of category B and C have implemented significantly smaller CSs. Their systems are usually integrated to enterprise resource planning (ERP) or product lifecycle management (PLM) systems, with little emphasis on external integrations to computer-aided design (CAD) or to advanced calculation systems. This indicates that with a minor configuration project for relatively simple products and not involving too many employees, the modelling can be managed by using less formal modelling tools. As the configuration task increase in both, size and complexity, the more important becomes a systematic modelling approach.

**4.3 Effects of the Configuration Set-Up on Companies' Performance**

Finally, the impact on the companies' ability to document and share their product knowledge, their ability to reduce the number of product variants in the company and the degree of employee satisfaction among the employees involved in the product configuration projects was investigated. The respondents have rated the impact on a five-point scale from 1 (strongly disagree) to 5 (strongly agree) and "empty space" for no answer to the question. Here, reducing product variants means the ability to eliminate unnecessary product variants from the product assortment in the company. The ability to keep down the number of product variants (item numbers) in the product assortment is claimed to be an important enabler for reducing complexity and thus keeping down costs in the company



**Fig. 6** Effects on work environment, knowledge management, product design and quality

[22, 23]. As listed in Fig. 6, A category companies claim to have a better ability to reduce the number of product variants than the others. This may be related to an increased ability to document and get access to product knowledge with the CRM procedure. Companies not using the CPM procedure report to have less documentation of, and access to, their product knowledge. However, the differences between the three groups on documentation and accessibility of product knowledge are not very significant. This could be related to the fact that the companies using less formal modelling techniques are having relatively minor CSs, which handle simpler configuration tasks and where the related complexity can still be managed.

Furthermore, employees working on product configuration projects with the described formal modelling procedure report to be slightly more satisfied with their working situation than those working with no formal modelling techniques. This may be related to the increased ability to document and get access to product knowledge, which makes it easier for the employees to control the product knowledge implemented in the CSs and to communicate the product knowledge with colleagues from other departments, such as product development, sales and production.

5 Conclusion

The conducted study on the use of product CSs in industrial companies provided new insight into how CSs are modelled and documented in relation to the nature of the configuration set-up. The results reveal that out of 18, six companies used



the suggested systematic modelling approach, namely the CPM procedure, for relatively complex products and sophisticated CSs. The remaining 12 companies used less formal or no formal modelling techniques for less challenging and less advanced configuration projects. Furthermore, three of the six respondents using the CPM modelling techniques have claimed that they started to use the more formal modelling techniques as the number of CSs and thus the configuration projects grew bigger and involved more and more people. They then claim to be more in control of their product knowledge and their product variants than the companies using less formal modelling techniques. This may be partly due to an increased ability to involve domain experts in the modelling process, which secures that the right decisions are being made as to which product variants to include in the CSs. This indicates that in order to major companies to be successful in the use of product CSs in a setup with several CSs with a high complexity and numerous employees (often geographically diversified) involved, a formal modelling technique like the CPM approach is needed. Furthermore, a more formal modelling technique makes it possible to keep track of the product variants, features and rules implemented in the CS. A better communication with the domain experts reflected in the report an increased ability to control the product knowledge as well as an increased level of satisfaction from the employees working in the configuration projects. The study revealed an important correlation between the use of a formal modelling technique (the CPM approach), the size and complexity of the CSs as well as the ability to control the product knowledge and products variants. However, having obtained these results, further questions are being raised as to, e.g. which specific features of the modelling techniques leads to an increased control of the product knowledge, or what is the correlation between the use of a formal modelling technique and the capability to successfully implement a product CS. Moreover, to better generalize the results, it would be beneficial to expand the number of industrial cases.

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## APPENDIX G

# Utilizing platforms in industrialized construction

## A case study of a precast manufacturer

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### Abstract

**Purpose** – The purpose of this paper is to explore the development of a platform-based project execution in the industrialised construction sector, with a focus on systematically balancing cost and value. Offering custom-tailored buildings at reasonable costs has been a growing concern for many construction companies. A promising approach adapted by operations management and design theory regards individual building projects as the adjustment and recombination of components and processes from a set of predefined platforms, while configuration systems assure feasible building solutions.

**Design/methodology/approach** – After adapting some of the underlying assertions of platform design to the engineer-to-order (ETO) situation in construction, the practical implications are evaluated on a case study of a precast manufacturer using high performance concrete.

**Findings** – Based on empirical findings from three distinct platform strategies, this research highlights key aspects of adapting platform-based developed theory to industrialised construction. Building projects use different layers of product, process and logistics platforms to form the right cost – value ratio for the target market application, while modelling methods map structural platform characteristics so as to balance commonality and distinctiveness.

**Originality/value** – This paper proposes a general theory of platform-based development and execution in the industrialised construction sector, which goes beyond concurrent approaches of standardising and systemising buildings projects. It adapts and extends established frameworks for platform development to the ETO situation in construction and empirically validates their cost and value effects.

**Keywords** Value, Platform, Engineer-to-order, Industrialized construction, Mass customization, Postponement

**Paper type** Case study



### Introduction

Various attempts have been made to face the diverse challenges in the building sector. Offsite manufacturing and the creation of systematic procedures and standardised building elements enforced the industrialisation of the sector since the middle of the 19th

century (Finnimore, 1989). The potential benefits from an industrial building environment are many and diverse (Blismas *et al.*, 2006). Zabihi *et al.* (2013) for example, argued that with offsite manufacturing, capacity and quality could be increased, while simultaneously offering more complex building components at a lower cost. Time-related advantages with regard to the production and erection of buildings are, for instance, discussed by Sacks *et al.* (2004) and Jaillon and Poon (2009). Other potential improvements involve the reduction of construction waste (Lachimpadi *et al.*, 2012) and a lower environmental impact and higher sustainability performance (Chen *et al.*, 2010).

The delivery of industrialised building systems has more recently been seen as a means for additional productivity advancement (Jansson *et al.*, 2013; Thuesen and Hvam, 2011). The building is seen as a set of major systems like walls, roof and foundation, where enterprises within on-site erection and offsite production of products and components mutually contribute to the construction project (Lachimpadi *et al.*, 2012). Thuesen and Hvam (2011), for example, investigate how system deliveries can lead to efficiency improvements of the German on-site construction. Their study shows how standardised procedures, preferred building solutions, and the reuse of experience and working groups (logistics platforms) have gained significant cost reductions on a number of housing projects without sacrificing customer value. Similarly, Jansson *et al.* (2013) study the advantage of delivering systems building as opposed to individual components. The authors examine the reuse of common processes and technical solutions across a number of building projects. Their effect on the design phase of two case companies has further been discussed in relation to the platform categories defined by Robertson and Ulrich (1998).

Competing with building systems which share common platforms provides a promising alternative to the mere standardisation strategy of traditional industrialised construction. Apart from systemising procedures and reusing technical specifications, in many industries the multi-product strategy of a platform approach has led to additional productivity and flexibility advantages. Early contributions see companies' product structure as a main driver for a platform implementation, emphasising the definition of a product platform as a set of common components or modules from which derivative products can be efficiently developed and launched (Meyer and Lehnerd, 1997). Baldwin and Clark (2000) define three distinct characteristics of a product platform, a modular architecture, the interfaces and the standards, which form design rules to which the modules conform. The prevailing approach to platform development is, therefore, to develop methods, tools and algorithms in support of the physical product family modelling (Yigit *et al.*, 2002). Moreover, Robertson and Ulrich (1998) point out that product platforms represent more than the physical structure of a product, but rather a collection of assets, which are common for a set of products. This holistic view has also been discussed by Jiao *et al.* (2007). The authors argue that a platform design can be seen as defining a set of common elements along the entire value creation process of a product or project respectively.

### *Research aim*

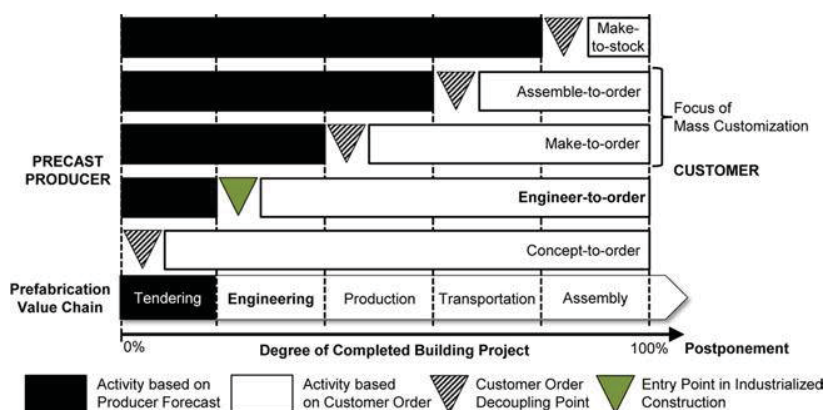
The aim of this research is to explore the potential of a platform-based product development approach within industrialised construction, in particular, represented by the precast sector as a major actor within the industry (Sacks *et al.*, 2004). This paper is formulated as follows. First, existing platform frameworks are adapted on the

engineer-to-order (ETO) situation of the precast industry. A heuristic view to platform design and modelling for building projects is introduced and its impact on the precast value chain is discussed relative to different manufacturing strategies. Next, a case study of a precast concrete manufacturer is presented, where the proposed methods are being applied and their operational impact on the precast value chain is being discussed. The paper concludes with the benefits and limitations of the proposed approach.

### Customising building projects with platforms

Research in construction has a long tradition in comparing and adapting related approaches from other industry sectors, like car production. Several authors have investigated the potential of such cross-industry learning, where significant benefits on industrialised housing could be proven (Barlow *et al.*, 2003). A key lesson from the automotive industry is the ability to provide a higher degree of customisation without compromising lead times, quality and costs (Parry and Graves, 2008). What became known as mass customisation aims at using configuration systems, adjustable product structures, flexible processes and adaptive organisations around a predefined set of platforms to efficiently offer custom-tailored products (Su *et al.*, 2005). To explore the potential for platforms, manufacturing companies are classified according to the customer order decoupling point (CODP), i.e. the degree the manufacturing setup is customer-independent and based on forecast or order-related and connected to a specific sale (Sharman, 1984). Wikner and Rudberg (2005) categorised the most commonly mentioned strategies throughout literature as ETO, make-to-order (MTO), assemble-to-order (ATO) and make-to-stock (MTS). In the context of construction, concept-to-order (CTO) is in addition used to describe a situation in which a customer is strongly involved already at the early conceptual phase of a building project (Winch, 2003). Taking the example of a building, by engaging with, e.g. the architect, in a CTO situation the customer then actively shapes the conceptual building scheme from the beginning, without, in particular, basing his ideas on a predefined structural or feasibility concerns (Mora *et al.*, 2008). Empirical examples can be found in one-off projects, where uniqueness of design is more important than productivity or functionality (Hobday, 2000). In an MTS strategy, on the other hand, the customer enters the process at a very late stage of its value creation. This strategy makes use of market forecasts to convert raw materials and components all the way to final standard products in accordance to expected customer demands. Between those two categories there are MTO and ATO firms which allow a certain degree of customisation based on the standardisation level of their products, like, for example, the previously mentioned car manufacturers.

In relation to the CODP, the precast supplier can be classified as an ETO manufacturer providing industrialised building systems (Zabihi *et al.*, 2013). As a common characteristic for ETO firms, the value chain consists of a non-physical stage involving marketing, tendering and engineering activities and a physical stage which concerns production, transportation and on-site assembly (Bertrand and Mu, 1993). The schematic representation in Figure 1 indicates how the customer enters the engineering phase of the value chain after completing the tendering process for a project. Starting from there, all subsequent phases, including producing the concrete elements, shipping and assembling them on the construction site, can be directly related to a particular customer or client order.



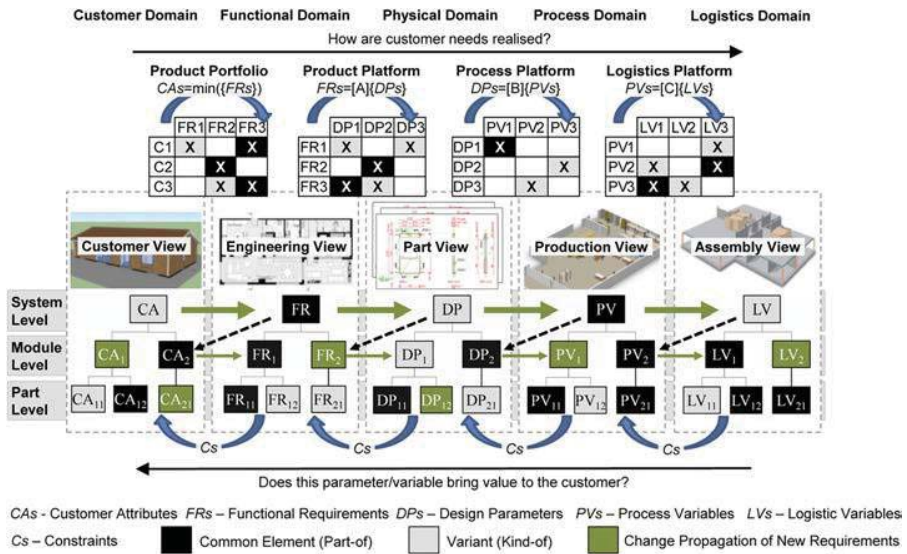
**Figure 1.**  
The CODP model in  
relation to the value  
chain of a precast  
manufacturer

To achieve mass customisation, companies coming from an MTS strategy need to move towards an ATO production (Wortman *et al.*, 1997). On the other hand, ETO companies need to accept a higher level of product and/or process standardisation, while postponing the COPD further down the value chain (Haug *et al.*, 2009). In avoiding this trade-off and moving the equilibrium point to a higher flexibility and productivity level, companies are utilising platform concepts to balance the required level of standardisation, while maintaining the desired flexibility throughout the value chain (Jiao *et al.*, 2007). Hence, a key objective of a platform-based product development is to provide sufficient product variety to meet individual customer needs while maintaining economies of scale and scope within manufacturing (Pine, 1993).

#### *Platform modelling framework for building projects*

Figure 2 illustrates a holistic approach to product family design through platforms throughout the value chain of a building project. The framework comprises five domains; customer, functional, physical, process and logistics domain. The customer domain involves the development of customer insight, where marketing techniques are used to determine customer attributes (CAs), i.e. requirements in relation to the market (Meyer and Lehnerd, 1997). Apart from requirements directly coming from the customer, there are a number of stakeholder requirements and governmental regulations that need to be fulfilled as well (Stevens and Martin, 1995). For ETO firms, the nature of the requirements tends to be specific and technical (Rahim and Baksh, 2003). In the building sector, they are often related to the building design and its different levels of details (Kiviniemi, 2005). As building regulations evolve, house builders and offsite manufacturers have to keep compliance and quickly adapt to new demands (Pan *et al.*, 2007). Once identified, common requirements can be grouped together to form consistent value prepositions for different market segments and to grade the impact the stakeholders have on them (Simpson *et al.*, 2011). CAs are then converted into a minimum set of functional requirements (FRs) in the functional domain as  $CAs = \min(\{FRs\})$ . Here architects traditionally develop building concepts from the customer information in an architectural design, based on existing industry norms and standards and available product technologies. The architectural design includes overall parameters of a building and architectural preferences on, e.g. materials, shapes and





**Figure 2.**  
Holistic view on  
platforms in  
industrialised  
construction

**Source:** Adapted from Jiao *et al.* (2007)

styles or increased energy efficiency. In platform terms, this mapping constitutes the definition of a product portfolio with a number of product families through which common practices of order configuration and sales automation with configuration systems are performed (Jiao *et al.*, 2007).

Mapping the relationships and interfaces of FRs to design parameters (DPs) is done in the physical domain and encompasses the definition of a product architecture as  $FR_s = [A]\{DP_s\}$  (Suh, 2001). Engineers transfer the initial design intent of the architect into a structural model with the objective to create feasible structure solutions, while referring to given architectural patterns and constraints. Such decisions are mostly based on the engineer's knowledge and experience of the realisation of the design intents on a given situation. With the structural analysis and the determination of the building behaviour of the preliminary design, the design focus changes from the innovative design intent of the conceptual design to a design task on a routine basis (Mora *et al.*, 2008). A process architecture can be defined accordingly as the mapping of the DPs to process variables (PVs) in form of  $DP_s = [B]\{PV_s\}$  and logistics variables (LVs) as  $PV_s = [C]\{LV_s\}$ , respectively. The last two domains traditionally involve the creation of common manufacturing processes, production technologies and distribution networks (Meyer and Lehnerd, 1997). Common production tools, machines, transportation resources and assembly methods can be used to reduce manufacturing set-up risks and to reuse proven production and assembly processes (Sawhney, 1998). From a precast perspective, the main concern is the transformation of design specifications of a building into physical precast elements and their subsequent on-site assembly.

In an ETO situation, developing well-functioning relationships among teams and team members is particularly important. Sales, engineering and production activities



are traditionally rarely standardised and rely on specific skills and craftsmanship. Extended coordination mechanisms are, therefore, used to balance product specifications with engineering and production capabilities for all upcoming orders (Konijnendijk, 1994). With the employment of stable teams within each stage of the value creation of a building, the precast producer can expect to benefit from economies of scope. The ability to produce and deliver the created building designs results in constraints (CSs), which have an upstream effect on the foregoing domains. Precast elements, for example, need to be lifted and assembled at the construction site. Build-in lifting brackets and mechanisms for assembly have to be designed and cast in place at the foregoing steps of the product realisation process.

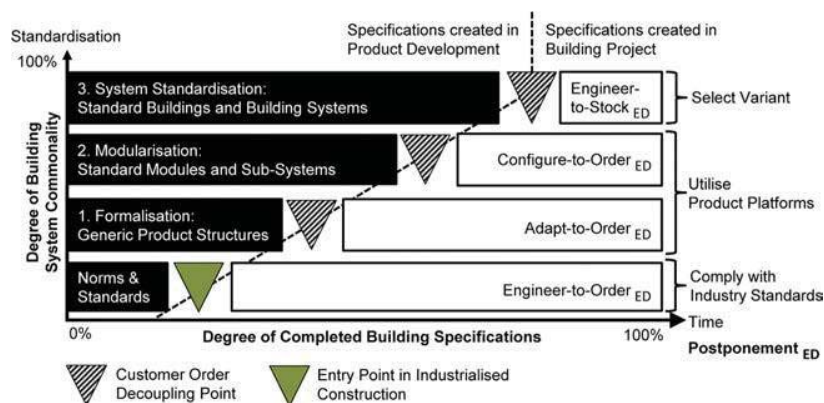
Modelling platforms from different perspectives through the so-called views facilitate the consideration of all five domains of a building project (Jiao and Tseng, 1999). As indicated in Figure 2, generic modelling notations are commonly used to represent hierarchies, commonalities (part-of structure), alternative varieties (kind-of structure) and ranges (Jiao and Tseng, 1999). Change propagation effects from newly identified building requirements can then directly be seen within the system (Clarkson *et al.*, 2004). The hierarchical classification of materials, parts, components and sub-assemblies represents the product structure (Do *et al.*, 2002), and is consistent with the common definition for bill of material (BOM) (Garwood, 1988). The different perspectives and relationships are modelled with the same notation, while their interrelations are mapped through direct connections and constraints for configuration. Most generic modelling approaches follow the basic principles of object oriented modelling using the Unified Modelling Language (UML) (Felfernig *et al.*, 2000). With their help, even complex product architectures, such as for ETO products, can be created (Brière-Côté *et al.*, 2010). Today, existing product lifecycle management (PLM) solutions obtain the same object-oriented hierarchical structure of a product (Mesihovic *et al.*, 2004). The overview of product structures with many component interrelations may be maintained with matrix-based modelling methods (Steward, 1981). The elements of such matrixes are simply listed in columns and rows and connections are made through the matching cells. Over the years, many related modelling methods and tools have been proposed in academia. With their relatively simple notation, Design Structure Matrixes (DSMs) have, for example, been developed to assess, reorganise and cluster relationships between functional or physical elements (Eppinger *et al.*, 1994). The methods have been applied on a number of product examples spanning from commercial to industrial products. To represent hierarchies of common and distinct elements in ETO platform designs, the matrix-based models are to be combined with the generic modelling techniques.

### *Platform effects on engineering*

ETO firms are by definition strongly concerned with engineering activities and how they are to be carried out in combination with manufacturing (Konijnendijk, 1994). To achieve the benefits from the use of platforms, they have to postpone the CODP to a later stage of the value chain, or, in other words, they have to accept a higher degree of predefinition of the subsequent tasks. Wikner and Rudberg (2005) point out the two-dimensional character of postponement for ETO firms. Apart from the production dimension, postponing the CODP can be seen from the engineering perspective as well. Based on contributions identified in literature, the authors conceptualise the extended two-dimensional framework of the CODP

and further describe the characteristics of a possible engineering-production mix in terms of postponement. Precast manufacturers are traditionally characterised as being engineer-to-order in the engineering dimension (ETO<sub>ED</sub>). They use the majority of their engineering resources for making building specifications on individual projects, while complying with industry-specific standards and norms. Their products obtain a low number of commonality, as the solution space communicated to their customers contains no explicitly formulated boundaries in form of catalogues from the beginning. Figure 3 depicts the link between the degree of standardisation from a building system perspective and its potential impact on placing the CODP in engineering.

The lowest level of system standardisation, i.e. formalisation, targets the part and component level. From a precast perspective such components are, for example, represented by different forms and dimensions of iron bars, insulation materials, concrete recipes, etc. The formalisation process includes the creation of a formal product family model containing generic product structures of the domains. Through product development, precast manufacturers need to agree on a common solution space for their product families, where, for example, possible precast element dimensions, load bearing capacity, dimension and placement of recesses or different materials and surfaces are mapped. The objective of this stage is to make an explicit documentation of possible variations, calculations and restrictions for a given family, without necessarily reducing the functionality and, respectively, the variety given to customers. By formalising the product portfolio, the precast producer is able to reuse the product knowledge on each building project more systematically and adapt-to-order (ATO<sub>ED</sub>), the building specifications within the boundaries of the established solution space. Knowledge-based engineering (KBE) systems can then be used to integrate the formalised technical product knowledge with the order-fulfilment process and, thus, to promote gains from knowledge reuse and sharing (Stokes, 2001). In literature, several attempts to increase organisational capabilities within the construction sector through IT system support can be observed, for example, Udeaja *et al.* (2008), Rezgui (2001) and Nitithamyong and Skibniewski (2004). In an ATO situation, so-called product configuration systems are used to streamline the sales and quotation process of customised goods in satisfying the



**Figure 3.**  
Leveraging the  
platform strategy  
through different  
decoupling points in  
engineering

Source: Adapted from Hvam *et al.* (2008)

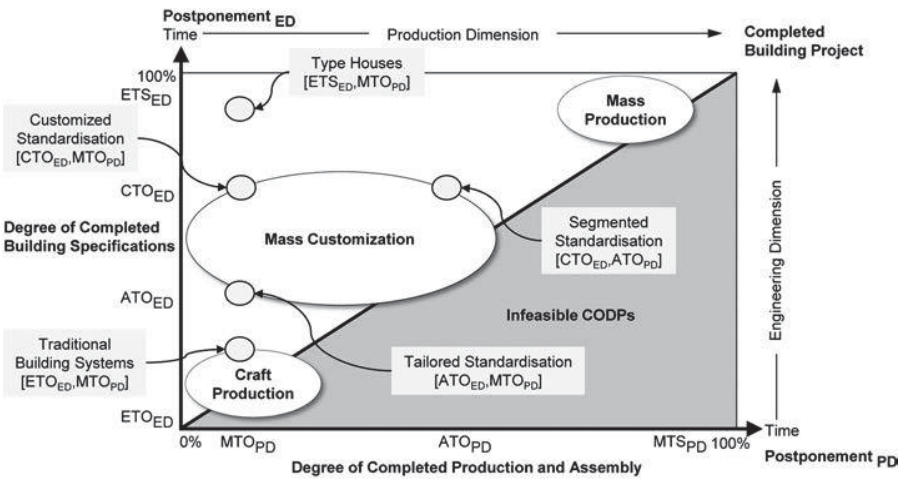
term  $CAs = \min(\{FRs\})$  (Salvador and Forza, 2004). For ETO sectors, such systems are, moreover, helpful to partly automate some of the subsequent engineering activities in assistance of  $FRs = [A]/\{DPs\}$  (Hvam *et al.*, 2008). However, comparable achievements in coordinating the specification process in construction have not yet been reported.

In Level 2 standardisation, engineers may define a standard set of building modules or subsystem variants, like different types of facades, which can be commonly used within the precast families. The various modules and sub-systems would be reconfigured for each building project through a configure-to-order ( $CTO_{ED}$ ) approach. At Level 3, standardisation finally refers to the development of entire standardised buildings or building systems, as, e.g. a pre-defined set of walls to an entire house type. Because all product specifications for a building project are defined prior to the actual customer order, this strategy can be characterised as  $ETS_{ED}$ . Companies offering houses from a type-house catalogue are a good example for an  $ETS_{ED}$  strategy. The focus of using product platforms for mass customizing buildings lies between the continuum of  $ETO_{ED}$  and  $ETS_{ED}$ , where the precast manufacturer accepts a certain level of product adjustments on a module or part level in the design based on individual customer needs. Empirical examples within related industries, such as for mass-customized timber houses, can, for example, be found in the Japanese housing market as discussed by Gann (1996).

#### *Combined platform effects on the precast value chain*

As argued by Wikner and Rudberg (2005), several feasible interrelations of a combined engineering-production CODP-mix can be defined. Figure 3 illustrates how two-dimensional placement of the CODP can be applied to the building industry. Precast firms are traditionally utilising a craft production approach in form of  $ETO_{ED}$  combined with a make-to-order in the production dimension strategy ( $MTO_{PD}$ ), or in short a [ $ETO_{ED}$ ,  $MTO_{PD}$ ] strategy. In contrast, the  $ETS_{ED}$  strategy of type-house providers is used in combination with the MTO production dimension as [ $ETS_{ED}$ ,  $MTO_{PD}$ ]. Even though for type-houses all building specifications are already defined in the product development phase, the production of walls, for example, would not start unless an order has been placed. According to the CODP definition, mass produced buildings with a [ $ETS_{ED}$ ,  $MTS_{PD}$ ] strategy would be created entirely based on forecasts; in other words, they would be pushed to the market without any consideration from customers or clients. As identified in Figure 4, the mass customisation area covers the remaining mix of feasible engineering and production mix approaches. The Japanese timber house market can be used as an analogy for the empirical evidence of the proposed strategies. Sekisui House, for example, follows a so-called “tailored standardisation” approach with an [ $ATO_{ED}$ ,  $MTO_{PD}$ ] strategy. The company uses standard components which are mainly produced on demand and adopted to customer requirements. The on-site assembly is done by specially trained subcontractors (Gann, 1996). Another mass customisation example in construction is represented by Sekisui Heim (Barlow *et al.*, 2003). The company makes use of a “standardised customisation” strategy through an [ $CTO_{ED}$ ,  $MTO_{PD}$ ] approach, where standard modular steel and timber frames around rooms are created offsite only few days before delivery. The modules are then directly shipped to the building sites for further assembly. An example for a [ $CTO_{ED}$ ,  $ATO_{PD}$ ] strategy can be found on Toyota Homes. The company utilises a so-called “segmented standardisation” approach, which is comparable to Toyota’s car production. Modular

**Figure 4.**  
Leveraging the platform strategy through a two-dimensional placement of decoupling points



**Source:** Adapted from Rudberg and Wilkner (2004)

units are produced based on forecasts without any significant input from customers. Customisation is then performed in the on-site assembly process, where modules are recombined and adjusted to particular housing needs. All three approaches make use of process and logistics platforms to significantly reduce the time and resources for manufacturing and on-site assembly. According to Gann (1996), having modules requires 50 per cent less labour cost for the on-site assembly process. At the same time, up to 55 per cent assembly lead time compared to traditional pre-fabricated panel houses or up to 67 per cent compared to a carpenter-built building are being saved. Therefore, the companies are able to combine a high degree of tailoring from their customers and clients with a stable delivery quality. To achieve the required productivity, the individual postponement strategies are further supported by innovative offsite manufacturing practices, which are comparable to assembly lines car manufacturers.

### Research methodology

Despite the potential advantages of the derived platform approach, its embracement in industry has been limited (Barlow *et al.*, 2003). This may be explained by the lack of empirical evidence and detailed explanations on how are platforms being developed and implemented through the value chain and what operational and monetary effects can, thereby, be observed. Acting upon this hypothesis, this paper uses a case study approach on a precast concrete manufacturer to better understand the complete phenomenon in its natural settings and to answer the question of why, what and how platforms are being developed and implemented in the precast industry (Benbasat *et al.*, 1987), as a representative example of the industrial building sector. This in-depth investigation requires a longitudinal research approach, often conducted in a single case to increase the opportunity of achieving meaningful observations (Voss *et al.*, 2002). The case company was selected based on two criteria:

- (1) its current financial performance and market share; and
- (2) its ability to develop and implement a platform strategy, which is independent and thus more stable from any particular building project.

The company represents a consortium of two separate organisations – an architecture firm and a major precast concrete manufacturer – offering precast sandwich elements and foundations mainly for the Danish market. This joint venture was established with the purpose of developing the engineering, production and assembly of pre-fabricated high-performance concrete (HPC) elements, allowing the innovation process to be studied in real time.

The unit of analysis was set on four product families, consisting of one traditional precast family and three HPC families, each following a distinct platform strategy. As literature within construction remains vague on this topic, quantitative analysis methods were supplemented with qualitative research in form of interviews. The purpose of the interviews was to gather additional empirical insight into the applicability and impact of platform-based product design of precast elements. In total, 45 supporting research interviews with 35 interviewees were conducted between 2011 and 2013 at the case company, its stakeholders and collaborating industry experts. A particular focus was laid on the practical implementation of the platform framework, including the discussed modelling methods for platform design. Each interview was semi-structured, to allow the flexibility of gathering additional insight throughout the interview process (Yin, 2009). The variety of professions, such as project management, structural engineering or marketing, enabled a more consistent coverage of the entire value chain. The results gained from the interviews served as a starting point for the subsequent analysis of the platform approach and a feedback mechanism for the development progress. In addition to that, the researchers were given access to all product family specification data, such as project offers, production drawings and cost figures within the stated period of two years. The realised impact of the platform use for the HPC product family was compared to the use of traditional concrete elements that are produced by precast manufacturer, where data from 45 projects performed in 2012 of traditional concrete elements and six projects from 2011 to 2013 with HPC products was investigated. The inspected data were triangulated against the interviews, where in a second round of mismatches were addressed.

## Analysis and results

### *Formulating the HPC portfolio*

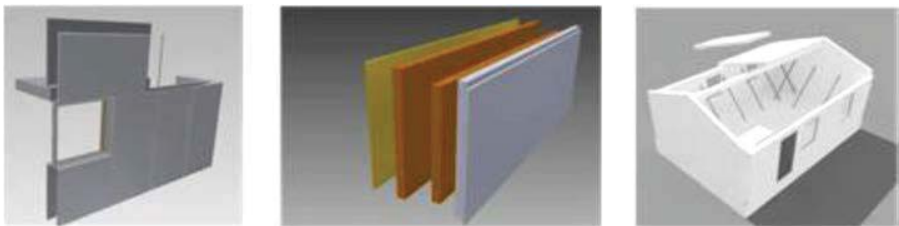
The development of the HPC product portfolio was initiated in 2010. Working on new concrete recipes, the organisation intuitively realised that many of the building challenges in developed and developing markets could potentially be addressed by using HPC as an alternative to, e.g. the traditional concrete, plaster or wood materials, already existing on the market. The company made an initial investigation on a number of markets both in Northern Europe and in developing markets in the southern part of Africa from a customer perspective. A series of CAs were formally listed, grouped and graded. A 5-point scale approach as defined by Martin and Ishii (2002) with 1 least important and 5 very important was used to derive general requirements from the CAs into concrete DPs. Moreover, the CAs' potential for propagation of changes within the system was graded based on the stakeholders' subjective preferences (Clarkson *et al.*,



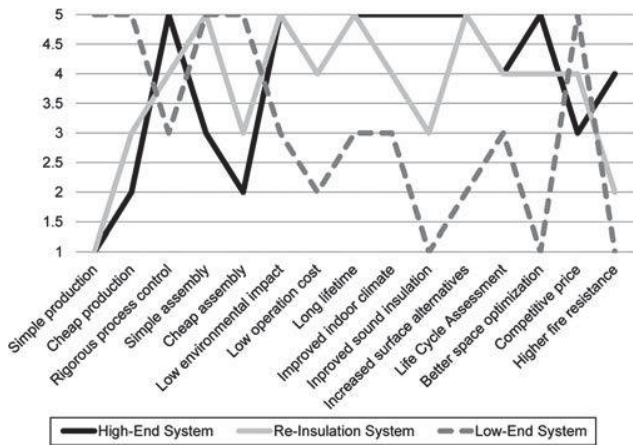
2004). From the initial grouping of the requirements, three different distinct product families could be formed: a high-end, a re-insulation and a low-end building systems (Figure 5).

Figure 6 displays the high-level list of CAs, the characteristic value proposition for each product family where the product family names indicate the intended market application. The design of the HPC high-end solution is closer positioned to the traditional elements. It targets the high-end market segment for customers who are concerned with buildings that obtain a unique surface design and aesthetics, better insulation, increased space optimisation and reduced CO<sub>2</sub> emission. The re-insulation system aims at competing with established products using metal or wood for re-insulating existing buildings. It utilises the same HPC material for offering re-insulation panels that, compared to existing solutions, have a longer lifetime, an improved surface design and variety and low operation cost, which are easy and cheap to assemble. The third building system targets the low-end market segment of shack dwellers, which are predominately to be found in developing markets. Based on the same HPC technology, this solution provides stable and long-lasting buildings with a reasonable quality at a competitive price and thus suggests a fundamental alternative to existing low-end housing today. Due to the special requirements for this market segment (Ofori, 2007), the low-end system is emphasising a strong focus on using local and often unskilled labour, cheap and simple production with predominantly local material and a simple and quick on-site

**Figure 5.**  
HPC product  
portfolio:  
re-insulation,  
high-end and low-end  
systems



**Figure 6.**  
Value proposition of  
the three product  
families with  
evaluated CAs



assembly. This explicit value proposition allowed the engineers to focus on aspects within each building system which generate a direct value to the customer, while limiting the non-value adding activities.

With the initial value definition for each product family, the design of the building systems was created in a close collaboration between architects and engineers. To compare the similarities and differences between the families, the traditional precast products are used as threshold values representing the current market norms for the industry. The result of the comparison is summarised in Table I, where for each product family the heuristic approach to platforms has been applied. The different views of the building system were modelled according to the generic modelling methods introduced by Hvam *et al.* (2008), while intra-domain matrixes were used to connect views.

#### *The product platforms used in the HPC portfolio*

The high-end HPC system consists of sandwich elements and their connection to each other and to other building systems, such as to foundation or ceiling. From an engineering perspective, the modified concrete recipe of the elements obtains a number of functional advantages compared to the traditional concrete elements, which facilitate fulfilling the objective of  $CAs = \min(\{FRs\})$ . In addition to an altered concrete material, a longer building lifetime has been obtained through a new joining system made from stainless steel. From a part view, with the high-end system the company focused on the value adding variety on the component level, while preserving the flexibility to meet all customer demands within the target market segment. Compared to traditional concrete elements, the high-end system uses fewer variants for reinforcing, insulating and connecting the sandwich elements, resulting in an overall higher part commonality of the system.

The re-insulating system utilises the same HPC material as the high-end solution. To conform to the requirements (FRs) of the re-insulating market, several additional DPs have been added. Instead of having a back plate made from concrete, a second layer of insulation material has been attached to the elements. A new mounting system ensures the fixation of the elements to the existing building, while a simpler jointing solution made out of stainless steel has been developed to seal the surface of the system. The re-insulation elements consist of a limited number of modules coming in different sizes. To ensure a high degree of flexibility, all modules use the same mounting and jointing system and can be combined and exchanged without affecting each other. Because the HPC material is more costly compared to the competitive products on the market made out of wood or metal, to reduce the cost of each element, unnecessary variety of the remaining parts has been lowered considerably. However, compared to the existing market standards, the additional variety of surfaces ensures the high aesthetic value of the overall re-insulation. For the low-end system, on the other hand, flexibility is less important than price. As all HPC building systems mainly share the same raw materials, the company must focus on standardising the low-end system as much as possible. It uses two different element types, roofs and surfaces in combination with common components to create entire buildings at a competitive price. The shape and size of the buildings can be modified, as elements can be moved, recombined or additional ones can be attached.

**Table I.**  
Overview of the  
platform strategy of  
the HPC portfolio in  
relation to traditional  
precast elements

Dimension	Traditional precast	High-end system	Re-insulation system	Low-end system
Product portfolio	Market average requirements for aesthetic, insulation, space optimisation, lifetime and environment	High requirements for aesthetic, insulation, space optimisation, lifetime, quality and environment; low requirements on price, easy production and assembly	High requirements for insulation, lifetime and assembly and space optimisation; moderate requirements for aesthetic and price	High requirements for surface design, easy and cheap production and assembly; moderate requirements on lifetime and environment; low requirements for aesthetic, insulation and space optimisation
<i>Product platform</i> Engineering view	Traditional concrete recipe, market norms for strength, load-bearing capacity, heat and sound insulation, lifting	HPC, increased capabilities in strength, load-bearing capacity, lifetime, heat and sound insulation, reduced CO <sub>2</sub> emission; redesigned joining system	HPC with the same characteristics as the high-end system; redesigned insulation, joining and mounting system	HPC with the same characteristics as the high-end system; redesigned joining and mounting system to other buildings
Part view	Part commonality at market norms; iron mesh with limited variety, multiple shear connectors, insulation materials, reinforcement, recesses, concrete recipes and surfaces	Increased commonality in element dimensions, common iron mesh, two shear connectors, two insulation materials, limited reinforcement, common concrete recipe, alternative additional surfaces and joining elements	Few common element dimensions, common fibre mesh, common mounting system to walls, two insulation materials, common reinforcement and concrete recipe, few surfaces, common joining elements	Two common element dimensions, common fibre mesh, shear connector, insulation material, reinforcement, recesses, and concrete recipe, two surfaces and roofs, common joining elements
IT support	No specification process support	No specification process support	No specification process support	No specification process support

(continued)



Dimension	Traditional precast	High-end system	Re-insulation system	Low-end system
<i>Process platform</i>				
Production view	Flexible processes, little mould commonality	Flexible processes, little mould commonality	Limited process flexibility, high mould commonality	Limited process flexibility, very high mould commonality
Team members	Unstable relationships	Stable relationships	Stable relationships	Stable relationships
Handover process	Little quality control, no formal handover procedures	Pre-defined end deliveries demanding for well-defined sub-delivery for each handover	Pre-defined end deliveries demanding for well-defined sub-delivery for each handover	Pre-defined end deliveries with less strict sub-delivery
IT support	Inconsistent data collection, no systematic learning	Centralised documentation, i.e. measurements, observations, sensors, tagging, quality control, central database	Centralised documentation, i.e. measurements, observations, sensors, tagging, quality control, central database	Centralised documentation, optional quality control
Continuous improvement	Long-term cycles	Short-term cycles	Short-term cycles	Mid-term cycles
<i>Logistics platform</i>				
Transportation	Little space utilisation due to weight restrictions for trucks	High space utilisation due to 50 per cent less volume and 70 per cent less weight	High space utilisation, comparable to re-insulation market norms	Maximum space utilisation with smaller trucks, due to 80-95 per cent less volume and weight
Assembly view	Crane size and assembly process according to market norms	Smaller cranes due to reduced element weight, higher requirements during assembly process	Smaller cranes due to reduced element weight, fast assembly process with standardized tooling, no scaffolds	Small cranes, more than 50 per cent less assembly time with standardized tooling
Team members	Unstable relationships	Stable relationships	Stable relationships	Stable relationships
Handover process	Little quality control, no formal handover procedures	Pre-defined end deliveries demanding for well-defined sub-delivery for each handover	Pre-defined end deliveries demanding for well-defined sub-delivery for each handover	Pre-defined end deliveries with less strict sub-delivery
Continuous improvement	Long-term cycles	Short-term cycles	Short-term cycles	Mid-term cycles
<i>Postponement strategy</i>				
Postponement view	Long-term cycles	Short-term cycles	Short-term cycles	Mid-term cycles
ETOed, MTOed, MTOpd	ETOed, MTOpd	ATOed, MTOpd	CTOed, MTOpd	CTOed, MTOpd

Table I.

*The process platforms used in the HPC portfolio*

In construction terms, the HPC product platforms exhibit a rather radical degree of redesign compared to the traditional concrete elements. From a production perspective, this difference is less obvious, as all three HPC building systems mainly go through the same production steps as the traditional elements. Yet, a cost and time advantage is achieved through reusing already existing production facilities, machineries, equipment and labour. Additional benefits arise with the higher degree of part and module commonality of the HPC portfolio, resulting in less flexible but at the same time more reliable and stable production steps. While for the high-end solution the effect from increased part commonality is smaller, the re-insulation and low-end elements strongly benefit from the standardisation attempts on the module level. Through the limited variety in dimensions, the company reuses a set of standardised moulds for casting and recesses made out of steel, thereby reducing waste and the need for resetting the production. Furthermore, the thinner dimensions and sharper edges of the HPC elements result in smaller production tolerances. To meet the increased quality demands, when working with HPC material, stable and well-trained teams have been created along with well-defined handover procedures for process deliveries. The high-quality standards are ensured with additional IT support for measuring, monitoring and tracking the entire production. A central database has been installed to collect and evaluate the acquired information. This constant quality control has led to shorter continuous improvement cycles of the HPC products and the way how they are produced.

*The logistics platforms used in the HPC portfolio*

A major advantage of using HPC instead of traditional concrete recipes is the reduced dimensions and weight of the elements. Transportation costs of the elements are typically responsible for 10 per cent of the cost of the entire building system. Therefore, reducing the costs of shipping the elements can have a big impact on the overall profitability of the building projects. This effect is exemplified on the high-end system. Here, the HPC sandwich elements have 50 per cent less volume and up 70 per cent less weight compared to traditional precast elements. In result, the company is able to better utilise the space of the trucks that are used for shipping and have considerable savings during assembly, which would otherwise be restricted by the weight of the elements. In developing markets, the reduced volume and weight of the low-end building system even accounts for 80-95 per cent. Smaller and lighter elements, in turn, make it possible to transport the elements with smaller trucks even through rural and unpaved areas. Another factor contributing to a lower price is that fewer variants of the product are offered based on the low-end product platform. From an assembly perspective, the volume and weight reduction of the HPC portfolio means that the company can operate with smaller and cheaper cranes at the building site. Moreover, with the re-insulation and low-end solution, the case company has introduced a new fast and simple assembly process, where standardised tooling is utilised for the entire on-site work. Apart from the benefits coming from smaller and lighter elements and standardised processes, a strong emphasis is being set on the employees and the quality of delivery. Comparable with the process platforms, stable and specialised teams are making sure that the predefined deliveries and all handover processes are being kept. Besides, the increased

transparency during assembly leads to shorter feedback cycles, allowing the company to continuously improve their procedures in shorter terms.

*Platform effects in the high-performance portfolio*

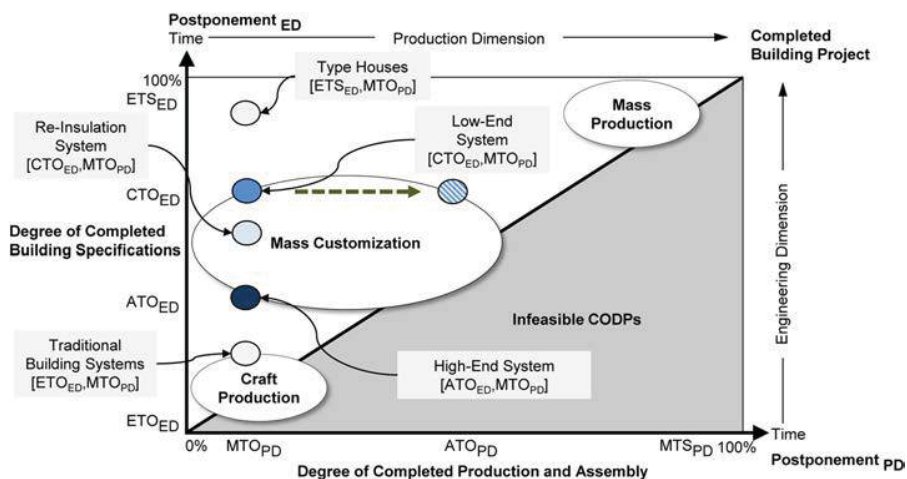
The platform analysis of the HPC portfolio demonstrates the potential advantage of focussing on the right balance between commonality and distinctiveness within each view of a product family. For the case, company an increased reuse of building specifications, machineries, tools and processes created in the development phase resulted in a higher degree of commonality along the value chain of a building project. Compared to a traditional precast project, an increased reuse capitalises in the ability to delay the differentiating activities of each project. Figure 7 depicts the postponement strategy of the three HPC product families. Depending on the intended positioning in the market, each product family is using the platforms to a degree, which allows placing the two-dimensional CODP according to the optimum cost-value relation. A traditional building project at the case company today requires, on average, three hours of engineering work per concrete element, once the detailed design of a building has been finalised. Having invested in formalising its offerings to the market, the high-end system, on the other hand, adapts systematically the building specification created during product development to the individual requirements of a project with an  $[ATO_{ED}, MTO_{PD}]$  strategy. The firm operates with the  $ATO_{ED}$  strategy within the boundaries of the assigned solution space in engineering, allowing for a higher level of flexibility in the subsequent production and assembly. While ensuring the desired delivery quality, the company strives in gaining economies of time throughout the specification process of the building, saving up to 20 per cent of engineering time for completing the building specifications. The effect of increased reuse of building specifications is even stronger for the re-insulation and the low-end systems, where up to 80 per cent of the overall engineering time is being economised. Both systems utilise a  $[CTO_{ED}, MTO_{PD}]$  approach, in which the benefits of having standardised modules take effect already at the conceptual design phase of the project. Even though formal product architectures have been established, at the time of the study, the case company has not invested in establishing a configuration system for any of their products. With the planned implementation of IT, additional positive lead time effects in engineering are expected. However, the observations indicate that the successful use of a configuration system support depends on how well the organizational changes are being implemented, rather than if such a system is capable of assisting the specification process.

The higher level of commonality along the entire lifecycle of the building project directs to additional reductions of lead times within production and on-site assembly. The additional benefits from using the platforms can be exemplified on the low-end system, where the standardised production processes report a 30-50 per cent lead time reduction. The redefined on-site assembly allows the company to use standardised tooling combined with lighter and smaller elements to assemble a single family building with three workers and one single tool in merely seven hours after having cast the foundation. With the ability to deliver quick and cheap housing, the company aims at directly addressing the growing housing demand in developing regions. As indicated in Figure 7, once access to new markets has been gained, scale-up programs are planned to increase the productivity of factories. By moving from a  $[CTO_{ED}, MTO_{PD}]$  towards an

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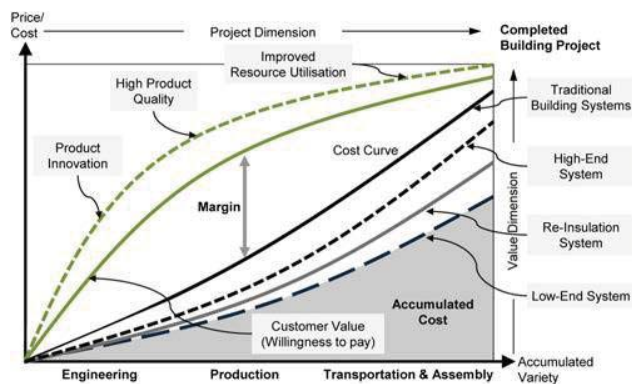
**Figure 7.**  
Platform leverage  
strategies for the  
HPC portfolio



IKEA model  $[CTO_{ED}, ATO_{PD}]$  strategy (Li *et al.*, 2011), the different wall elements can then be produced based on a forecast, reducing the delivery time of the building to the lead time of transportation and assembly. While staying within the boundaries of the building system, each customer is then able to order his configured house, based on an individual combination of the elements.

Apart from economies of time, with the platform strategies the company is bridging the paradigm of delivering the optimum cost – value relation for each HPC product family. Figure 8 illustrates the impact the utilised platforms have on the accumulated cost of the case company throughout a building project. While the higher flexibility of the high-end system results in a relatively high-cost structure which is close to the traditional building systems, it focuses on generating higher margins through a selective value proposition. An increase in material costs is compensated with savings in engineering, transportation and assembly, while the improved aesthetics and material properties add additional value to customers. Similar to the platform strategy

**Figure 8.**  
Economic  
implication of the  
HPC platforms in the  
case company



of car manufacturers (Proff, 2000), as discussed previously the re-insulation and low-end systems benefit from adapting product innovation, production technologies as well as better utilised resources during transportation and assembly of the high-end system to constantly improve their platforms. Furthermore, being more concerned with offering competitive prices, the two families focus on reusing their assets along building projects, where non-value adding variety is reduced to a minimum. This enforced simplicity, for example, lowers the cost of a low-end building to price points that are compatible to slack dwellers in development markets, yet using comparable materials and product quality as the high-end system. Finally, the overall platform strategy of the company has resulted in a number of patterns, which are used to secure their competitive advantage from the illustrated product and production innovations.

## Conclusion

Research in construction has long been focusing on adapting concepts and methods from other industries such as the automotive industry to bring forward industrialisation and to reach higher productivity levels. While the accommodation of lean principles has received much attention, fundamental methods for ensuring an efficient customisation of buildings have mainly been neglected. Mass customisation aims at bridging this gap of delivering customised products at near mass production efficiency. Successful mass customisers to be found in industry apply platforms as a means to acquire economies of scale while maintaining adjustable product structures, flexible processes and adaptive organisations. In addition, they use product configuration systems around their platforms in support of their specification processes. Scholars approaching this topic have to adapt the two principles to the ETO situation in construction and to present practical guidelines for their implementation.

In addressing the two issues, this paper has presented a holistic view of platforms as a framework for understanding how mass customizing building projects is being facilitated, in general. The study uses the precast sector as a representative industry to formalise the value chain of a building project in relation to the different manufacturing strategies according to the CODP. By drawing on theory in platform development, the application of a product, process and logistics platform has been explained on the example of a building project. To create the right balance between commonality and distinctiveness, relationships between the platform domains and the connection to market requirements have been expressed through generic and matrix-based modelling methods. Then, the two-dimensional postponement of the CODP has been used to synthesise the relevance of using configuration systems and to conceptualise the operational effects of platforms throughout the lifetime of a building project. Likewise, a cost – value concept has been introduced to explain the related economic implications.

The paper uses a mixed-method research design, from both qualitative and quantitative sources, to collect evidence for the holistic view on platforms within the precast sector and to validate the developed framework. The applied methodology facilitated the in-depth exploration of how practitioners from the industry take up the platform concept, what challenges they face and what benefits they realise. In the subsequent analysis, three distinct platform strategies from a precast manufacturer were compared to the otherwise traditional building projects. Each strategy was related to the previously introduced framework and discussed according to both its operational as well as economic implications. The obtained results demonstrated strong incentives

for implementing several feasible platform constructs within the precast industry. Moreover, the benefits from integrating configuration systems throughout the specification process of buildings were conceptually elaborated, for which, an enormous potential for future research has been recognised. Pragmatically, the findings suggest that utilising platforms does not necessarily imply sacrificing design flexibility and customer value, respectively, in favour of efficiency, but rather involves the creation of an optimum cost – value relation for the target market segment. This case study approach admittedly implies certain limitations with respect to generalisability and repeatability of the research. The increasing maturity level of the industry entails that essentially any major precast manufacturer operating in developed markets obtains few universal capabilities with respect to its value chain (Li *et al.*, 2014), and may, hence, be used as a basic representative example to test the introduced framework. On the other hand, as demonstrated a consistent platform approach requires a certain level of development effort to obtain the discussed two-dimensional postponed strategy. This innovation process has to be performed independently from any particular building project and involves the application of the discussed modelling methods (Brière-Côté *et al.*, 2010; Meyer and Lehnerd, 1997; Suh, 2001), which is, however, traditionally rarely the case within the building sector (Gambatese and Hallowell, 2011). Consequently, further empirically grounded research on a variety of building systems is needed to better understand the complementary effects of platform modelling, configuration system support and postponement, as a result of the introduced framework. This would increase the interest in mass customisation within house building and may further lead to a wider acceptance of the presented methods.

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## APPENDIX H

# Product platform considerations on a project that develops sustainable low-cost housing for townships

Michael Wörösch<sup>1</sup>, Martin Bonev<sup>2</sup>, Niels Henrik Mortensen<sup>3</sup>

## Abstract

Construction companies in Denmark are often working with profit margins as little as 1-3% in situations where they deliver high-end buildings to the local market. Even though customers are willing to pay a premium price for high quality, construction companies earn very little on their products. Consequently one Danish company took the decision to produce sustainable low-cost houses and to sell them to developing countries that have township housing programmes. But why would this company believe it could make a profit in the low-cost housing segment abroad, when there is almost no profit in the high-end segment at home? As the research described in this article shows there are three main reasons for their optimism: 1) The successful introduction of a product platform for low-cost houses, 2) a modular approach to the design of low-cost houses, and 3) the application of requirements management as described by INCOSE. 1) to 3) have been studied using action research on a case project.

The case company's success contributes to people currently living without decent housing by providing insulated, low-cost houses based on the latest technology. The fact that those low-cost houses are solid gives their new owners the possibility to take a loan out on their building which is expected to contribute to more businesses being started up and thereby strengthening the domestic economy. As a consequence of this, additional research is needed in how to further optimise the economy of sustainable low-cost housing based on life cycle considerations. Moreover, it has to be examined how the experience gained can support in maximising the high-end segment in countries like Denmark.

**Key words:** Low-cost housing, product platform, construction industry, practical implementation, action research

## 1. Introduction

This section will introduce the trend of population growth and the concept of product platforms which are core to the business opportunity of the research case detailed in this paper.

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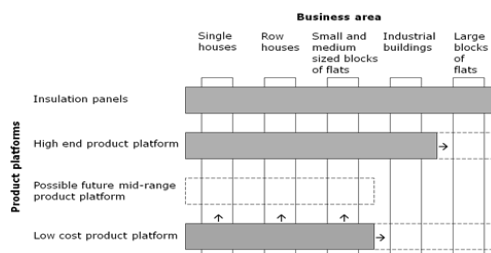
## 1.1 Population growth in developing countries

It is estimated that about 1.6 billion people around the world live in sub-standard housing and over 100 million are homeless. If no serious action is taken the number of slum dwellers is expected to rise from one billion people today to two billion within the next 30 years (Habitat for Humanity, 2013). This leaves many developing countries with a problem that is hard for them to overcome. South Africa is one of the countries that are taking action, as it tries to solve its housing problem by means of a centrally planned housing programme. Through this programme, since 1994 more than 2.3 million housing units have been made available to nearly 11 million people, where in 2010 alone about 219.000 housing units have been made. The goal for the coming years is to create 220.000 housing units a year. Despite such a tremendous number of erected units, the housing backlog has grown from 1.5 million units in 1994 to 2.1 million units today. This means that 12 million South Africans – a quarter of the population – are still in need of a better shelter (Ministry of national housing and social amenities, 2011).

Inspired by the housing programme of the South African government, the case company described in this article examined whether and how it would be possible to contribute to the housing problem of developing nations with its knowledge and technology. After a careful examination of the National Housing code (2009), the decision was taken to develop a low-cost product platform that could co-exist with both the existing, high-end and re-insulation panel product platforms and to make an offer to the South African housing programme.

## 1.2 Product platform definition and strategy

The product platform concept has widely been discussed in literature, where accordingly a number of definitions have been introduced by e.g. Muffatto and Roveda (2002). Halman et al. (2009, page 151) for example, refer to McGrath's definition of a product platform: "a set of subsystems and interfaces that form a common structure from which a stream of related products can be effectively developed and produced". The authors base their research on this definition, as it incorporates both the physical and economical aspects of a platform concept. An overview of the product platforms that exist in the case company can be seen in Figure 1.



**Figure 1: The product platforms that exist in the case company**

As illustrated in Figure 1, the insulation panels aim to cover all business segments, while the other two product platforms address only parts of the market, but still keeping the possibility

of expanding open. The reasons for believing in the success of a product platform that did not even exist at the time the offer was made were:

- The product platform approach had been rooted in the organisation and the staff of the case company had been trained in product platform thinking for several years
- The successful implementation of requirements management in the case company
- All the desired European safety and product approvals had already been received
- The technology the case company wanted to use had successfully been tried out in several buildings in Denmark (see Figure 2 for an example)
- The senior staff have a long history of successfully executed building projects

The above listed points indicate that a strong base had indeed been established which made it possible for the case company to continue building upon. At the same time the case company was also aware of the main obstacles that had to be overcome. To begin with, the government subsidy for a 40 m<sup>2</sup> stand-alone house only amounts to 55.706 ZAR (= 4.926,87 € using exchange rates from December 25<sup>th</sup> 2012) (Coetzer, 2010), which is considerably less than what a house based on the high-end product platform costs. Moreover, unskilled labour is to be used, whereas the usual approach of the case company is one of automation and efficiency in combination with a skilled work force. There is also a risk of facing problems using the local building materials with unknown properties and quality. However, the management of the case company had full confidence in being able to produce 40 m<sup>2</sup> low-cost houses at a price that did not exceed the government subsidy. Working with unskilled labour and having to use local building material were treated as risks. Therefore, risk mitigation plans were made for those two points as described in the PMBOK (2008).



**Figure 2: A building based on the high-end product platform**

Studying the situation resulted in the main hypothesis that creating and introducing a platform concept to low-cost markets would support both, developing countries in overcoming their housing problem in an effective manner, and construction companies to improve their performance in the domestic markets. To this end, this article in particular addresses the following aspects:

- a) It is possible and beneficial to develop a low-cost product platform that can be used for making low-cost houses
- b) It is possible to make several variants of houses based on that low-cost product platform

- c) The new knowledge gained by developing and implementing a product platform for low-cost housing will contribute to improved efficiency and reduced prices in the high-end platform

This paper therefore deals with the question on how to successfully introduce a product platform that supports modularity to the low-cost housing segment of the construction industry. To answer this question, after a literature review (Section 2), an explanation of the applied research and design methods (Section 3) and a description of the case (Section 4) will be provided. Section 5 then gives a brief overview on the key observations that have been made when developing the low-cost product platform and building houses. In Section 6 the thereby achieved results have been analysed. A final conclusion is drawn in Section 7, where the most important findings are summarised and recommendations for future research are given.

## 2. Literature review

Even though the work on the case project was mainly of a practical nature, a lot of knowledge has been drawn from literature, where both academic publications as well as literature from seasoned practitioners have been consulted. Table 1 below gives an overview showing the main references considered for this article and what they cover in the context of this research:

**Table 1: Main literature considered in this research**

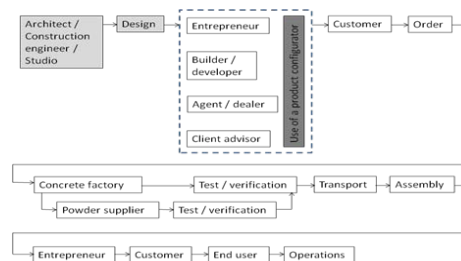
	Ulrich and Tung (1991)	Thuesen and Hvam (2011)	Mortensen et al. (2008)	Simpson et al. (2011)	INCOSE Systems Engineering Handbook (2011)	Huang et al. (2005)	Roy et al. (2003)	This article
Product platform		X	X	X		X	X	
Product platform in construction		X					X	
Product platform in construction – low-cost housing								X
Product variants / family	X		X	X		X	X	X
Modularization of products	X	X	X			X	X	X
Requirements management					X		X	

The concepts of product modularization (Ulrich and Tung, 1991) and product platforms have extensively been discussed in literature. Huang et al. (2005) for example have studied several companies in different industries using product platforms. In addition, Hvam (2011), Mortensen (2008), and Simpson (2011) provide a number of publications on the application

of product platforms, where the approach of using product platforms has mainly been put in the context of consumer electronics, car, aerospace, and software industries. However, at the same time very little theoretical contribution could be found on how to apply product platform principles to the construction industry (Roy et al., 2003). As of today, there are in particular no published attempts to practically implement a product platform which facilitates modularity and product variants for low cost housing in this industry.

### 3. Research and design methods

The research described in this article makes use of action research (AR) defined by Coughlan and Coughlan (2002) as well as Checkland and Holwell (1998) for creating the needed models and tools. The approach was applied to a case project, where full access to all key people and complete access to all documents relevant to this research, including minutes of meetings in addition to documents containing the future strategy of the case company and its products, existed (Voss et al., 2002 and Yin). In order to cover all parts of the case project's value chain (see Figure 3), including the sub-projects described in Section 4 "Description of case", several interview rounds with key persons from the construction industry and the case project have been conducted.



**Figure 3: The value chain of the case project**

For reasons of comparability and consistency interviews were conducted using a question template from previous research for all participants, resulting in a master document that covered a wide range of different requirements: from functional, non-functional, technical, market and organisational requirements, to requirements towards the project manager and finally to requirements of the stakeholders themselves. This was used to implement requirements management on the case project and was actually (at that time unconsciously) the first step towards a low-cost product platform. During the analysis of the second out of four AR cycles it became clear that requirements management on the case project worked well (Wörösch, 2012), as it significantly contributed to having a clearly defined scope of the case project, its sub-projects, and the different product platforms – the two existing ones as well as the one that needed to be developed.

When linking the requirements of the low-cost product platform to the company and product strategies, modularity of the houses based on this platform could be ensured. In an architectural perspective, a definition of the term modularity that fits well with this research has been described by Ulrich and Tung (1991). The authors refer to "the construction of a building from many instances of standardised components. In manufacturing the term often



refers to the use of interchangeable units to create product variants" (Ulrich and Tung (1991, page 73)). Examples of the hereby achieved modularity will be given in Section 6.

## **4. Description of case**

Despite of operating in construction, the case company is unique within its industry in several aspects. Firstly, it produces sandwich elements and insulation panels from High Performance Concrete (HPC) that are used to build and renovate houses to have greater energy efficiencies. Secondly, the company constantly develops new technologies and products resulting in patents. Therefore, already today, it offers buildings that live up to the European Union's 2020 energy saving requirements, covering the complete value chain (see Figure 3), where responsibility is not pushed down to sub contractors. The uniqueness of this case is reflected in the structure of the case project that consists of four different types of sub-projects, which will in the following section be shortly introduced:

1. Technology development used to develop new insulation and HPC material as well as different mounting systems
2. Product development with the goal to develop new sandwich elements, insulation panels, and jointing in different dimensions
3. Development of low-cost, high-end, and insulation panel product platforms
4. New building projects (such as the erection of 40 m<sup>2</sup> prototype buildings in Delft, Cape Town, South Africa)

1) to 4) deliver and share human and financial resources as well as processes, which simultaneously results in constraints, where 4) depends on the success of 1), 2), and 3).

## **5. Observations**

When developing the low-cost product platform and building the houses, a series of key observations, that are further grouped and described in detail, has been made.

### **5.1 The low-cost product platform**

- On a conceptual level there were many elements that could be re-used from the high-end product platform; e.g. the basic methodology when describing a platform structure and how to phrase requirements. Previously, there was not much reuse between the two other product platforms
- A solution for the design of the HPC elements has been found that required only few tools for assembly. Buildings can even be assembled without using power tools, since stable electricity sometimes is absent on some building sites. An assembly where only few tools are needed also makes teaching of staff easier and leaves less room for error
- Even though unskilled labour and no high technology production are being used, many houses can be produced during a year. This is due to the production of only few different kinds of elements, which are strongly standardised and can be used across the product variants. Using unskilled labour and no high technology also changes the

description of requirements from being database and specification focused to being expressed in photographs and drawings wherever possible

- Once the HPC elements with their pre-mounted windows and doors are ready for assembly, a Type 1 house (see Figure 4) can be assembled within one working day. This fast assembly also contributes to the possibility of building many Type 1 houses in the course of a year and at the same time it prevents theft or unauthorised occupation, as the houses are closed in the evenings
- The local building materials (about 99%) can be used without any quality problems. The only exception to the use of local material is a special concrete binder that is sent from Denmark. In result, the use of local material creates domestic jobs and reduces CO<sub>2</sub> emission that otherwise would have been caused by transportation from abroad
- The scalability of the low-cost platform is high. This means that when, for example, the production has to be doubled or halved it can be done relatively fast at low cost
- The price of a 40m<sup>2</sup> stand-alone house (basic model) based on the low-cost product platform does not exceed 55.706 ZAR. This means that the case company can continue building the low-cost houses without generating losses and the housing programme can accordingly achieve its yearly targets

## **5.2 Modularity**

Modularity has been achieved in several facets. For the customers this means that they can upgrade their houses with extra rooms, a veranda or a bigger kitchen at a low price at the time of ordering. Upgrading is possible in all situations where the housing programme facilitates a contribution of the end user. Besides, modularity can also be achieved by using additional means; e.g. by giving the customer or resident the possibility to enhance the house by adding a rainwater collector that gathers rain water from the roof facilitating cultivating a garden for the house. Another benefit of achieving modularity is that it also is possible to improve the houses with solar panels for generating power for hot water, lighting, charging computers, cell phones, and other consumption. Also, here the housing programme has to allow this kind of improvement.

## **5.3 Knowledge transferred back to the high-end product platform**

- The high degree of standardisation contributes to a high throughput in production. The high-end product platform needs to be examined for possibilities to increase standardisation and to get away from the current high level of uneconomic flexibility
- The use of prototype elements, drawings, and verbal explanations instead of lengthy documents has been very successful. This method of controlling the scope for a product platform could also be introduced to the other product platforms, which, however, would mean to go away from a systems engineering best practice approach as described in the INCOSE Systems Engineering Handbook (2011). It has to be examined to what degree this could be done while still maintaining sufficient documentation and living up to described processes
- The rather effective way of teaching new local staff and the team, created a very inspiring feeling during the teaching sessions and should further be applied to staff working on the other platforms as well. Flying the key personnel of the case project to

South Africa in order to participate in building low-cost houses could be one way of transferring the new knowledge and a positive team spirit back to Denmark

- This new knowledge gained by developing and implementing a product platform for low-cost housing will contribute to improved efficiency and reduced prices in the high-end platform, as many decisions that had been taken on the high-end product platform have been seriously challenged. An example is the very high focus on the factor cost for the low-cost platform that has never been enforced to such a degree on the high-end product platform

Having summarised the main observations, in the next section the results of implementing a low-cost product platform into the case project are discussed.

## **6. Discussion of results**

By the end of action research cycle two, the research conducted in the case project had given a series of theoretical and practical results. The main results have been listed below.

### **6.1 High level results of making a low-cost product platform**

As anticipated, from a technical and process point of view, it was indeed possible to develop the low-cost product platform and build houses based on it within the estimated time. Due to the active use of requirements management, the scope of the new product platform was clearly defined, while market segment-wise there was no overlapping with the existing product platforms. From a societal point of view, building low-cost houses at high speed helps ensuring that more people have decent housing and thereby producing an increase in quality of life. Furthermore, a relatively fast, cheap and secure assembly, contributes to reducing the large backlog in the low cost housing area. Thus, as demonstrated by the case company, local job opportunities together with relevant education and training are created. This increases the standard of living and improves future chances for personal development. Houses made from HPC are solid and have according to Danish Standard (2001) a minimum life expectancy of 50 years, while in practice concrete companies often calculate with 70 or more years. This is much higher than what most housing objects currently have. This longer life expectancy makes it possible for a house owner to take a loan out on their house, which in turn can contribute to starting up financial businesses and thereby to strengthening the domestic economy.

### **6.2 Results related to the main hypothesis**

#### **6.2.1 The low-cost product platform and the use of modularity**

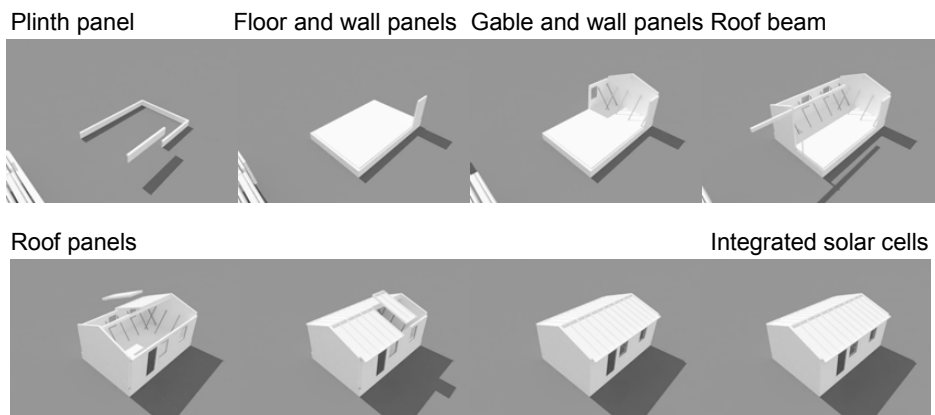
The low-cost product platform currently supports three types of houses, of which two will be explained further in this paper. All houses based on this platform can only be ordered in a light or in a dark version. Each of them comes with two different surface structures, a smooth and a brick-like one. Altogether the customer is offered a limited number of choices, as all concrete elements, windows, doors, materials, sizes, and interfaces are completely standardised. This radical standardisation is the main difference from the high-end product

platform, for which more variety and a higher degree of customisation is available. Figures 4 (Type 1) and 5 (Type 2) show two types of 40m2 houses, that are based on this new low-cost product platform.

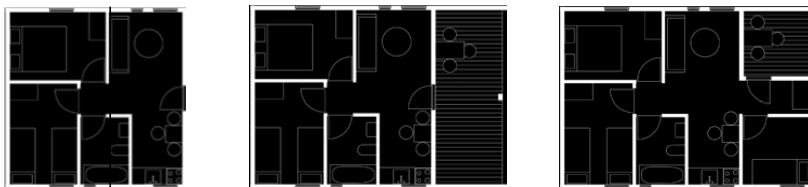


**Figures 4 and 5: Two different 40 m2 buildings made from HPC – Type 1 and Type 2**

Modularity on the low-cost product platform exists on two levels. On the element level, the HPC elements are prefabricated and scaled to approximately 1,2m in width. Figure 6 illustrates the conceptual assembly of a Type 1 house based on those elements. On the building level, several variants of the Type 1 and Type 2 house exist. The Type 1 house can be produced as basic 40 m2 model or as one of four variants, where modules like a veranda or extra rooms can be added. Depending on what modules are added, the size of a Type 1 building can go up to 56 m2, as depicted in Figure 7.



**Figure 6: A Type 1 house assembled from prefabricated HPC elements**



40 m2 basic model + 2 modules veranda 40 m2 + 2 modules veranda, extra room 50 m2



+ 2 modules veranda, larger kitchen 50 m<sup>2</sup> + 2 modules 2 extra rooms 56 m<sup>2</sup>

**Figure 7: The five variants of the Type 1 house (Figures 6 and 7 have been taken from a sales offer to the South African Housing Programme)**

### 6.2.2 Knowledge transferred back to the high-end platform

A lot of knowledge has been gained when making the low-cost product platform. Some of the key learning points were:

- Even though there were only a few choices the customers could make, when ordering a house, the offered variety appeared to be suitable for this market segment. This will result in a review of the high-end product platform, to ensure that customers are not offered an infinite degree of variety and that the financial contribution per variant is high enough. Non-profitable variants should be removed from the platform
- Starting the low-cost product platform from scratch, rather than trying to take the high-end product platform as a starting point for scraping off layers, turned out to be the right decision. In hindsight, it is our belief, that it would not have been possible within the given timeframe to achieve the cost goal per unit using this approach
- This was the third product platform the case company developed. Since the high-end and insulation panel product platforms were well defined and linked to the company strategy, developing a third product platform took considerably less time. The experienced staff and the right software tool support, such as the use of product configuration systems (Bonev and Hvam, 2012), contributed strongly to the fast development of this platform

## 7. Conclusion

In this article it has been described how a low-cost product platform has successfully been developed and implemented in the low-cost housing segment within the construction industry. The houses based on this platform are built up in a modular approach, where modularity has been achieved both on element and on building level, resulting in buildings which can be delivered in several types and variants. The main difference compared to a coexisting high-end product platform is the high degree of standardisation and the limited number of commercial variants, which has been adapted according to the requirements of this market segment. Besides, the application of requirements management as described by INCOSE has resulted in working descriptions containing much less text, but with more pictures and drawings instead. This positive attempt to use product platforms in the low-cost segment of the construction industry confirmed the main hypothesis of this research (Section 1) and shows that the product platform approach is a valid strategy for meeting the low cost

housing demand of developing countries. Hopefully the described case inspires other construction companies to introduce a product platform concept for their products.

Despite the promising results, further research is needed in the following vicinities: Since there is a high need for decent housing, smart solutions have to be found for quickly producing a high amount of houses, which are cheap and long lasting. If companies find a way of addressing this issue in a profitable manner, they are more likely to participate in this enormous task. At the same time it is important that the applied housing solutions are sustainable, as according to EU, 2010, residential and commercial buildings are responsible for about 40% of the total energy consumption and 36% of the total CO<sub>2</sub> emission in the European Union. Other parts of the world will soon face similar situations to those described above, if there is no sufficient focus on sustainability when producing such a vast amount of buildings. To this end, further research is needed in how product platforms, by means of effective development and production, can further contribute to the low-cost housing segment and to the construction industry in general. Finally, it is necessary to further optimise the economy of sustainable low-cost housing based on life cycle considerations. Once this has been done, it has to be examined how the gained experience can support in maximising the high-end segment in countries like Denmark.

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## APPENDIX I



# **EXTENDING PRODUCT MODELING METHODS FOR INTEGRATED PRODUCT DEVELOPMENT**

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## **ABSTRACT**

Despite great efforts within the modeling domain, the majority of methods often address the uncommon design situation of an original product development. However, studies illustrate that development tasks are predominantly related to redesigning, improving, and extending already existing products. Updated design requirements have then to be made explicit and mapped against the existing product architecture. In this paper, existing methods are adapted and extended through linking updated requirements to suitable product models. By combining several established modeling techniques, such as the DSM and PVM methods, in a presented Product Requirement Development model some of the individual drawbacks of each method could be overcome. Based on the UML standard, the model enables the representation of complex hierarchical relationships in a generic product model. At the same time it uses matrix-based models to link and evaluate updated requirements to several levels of the product architecture and to illustrate how these requirements have an upstream (towards stakeholders) and downstream (towards production) effect on the product architecture.

**Keywords:** Product Modeling, Requirements, Integrated Product Development, Product architecture, Product Variant Master

# 1 INTRODUCTION

## 1.1 Background

In today's global market competition, manufacturing companies are forced to keep up quickly with a dynamically changing competitive environment. Launching innovative products in accelerating development cycles becomes a crucial competitive advantage (Meyer & Marion, 2012). In order to achieve a high productivity in their product development (PD) process, firms are under pressure to employ suitable tools and methods, which allow an in-depth understanding and managing of knowledge related to the products, processes, but also to the project environment (Cooper & Edgett, 2008). To this end, both researchers and practitioners have put much effort in developing structured approaches on how to make the process of PD more efficient and thereby to reduce the development time and accomplish more successful results. Standardized procedures, methods and notations have been introduced, aiming at improving the management and collaboration of product development projects. Pahl & Beitz (2007) and especially the VDI-Guidelines 2221-2222 e.g. describe a stepwise procedure for product development, starting from identifying the design requirements to modeling the detailed design. The design process is hereby divided into individual steps, which can partly be performed in parallel (Simultaneous Engineering), while keeping a close contact to customers and suppliers. Similarly, Ulrich and Eppinger (2012, p. 2) define product development as a "set of activities beginning with the perception of a market opportunity and ending in the production, sale, and delivery of a product". Traditionally, these phases are performed separately and sequential, except for the detailed design step, which usually includes a number of internal iterations (Unger and Eppinger, 2011). In Concurrent Engineering (CE) all requirements products need to satisfy throughout their life cycle are captured already in the planning and concept phases. Since the majority of the cost is determined at this early stage of the design process (Whitney, 1988), having an overview of the complete lifecycle of a product may reduce all related cost from purchasing to product delivery significantly (Anderson, 2003). Accordingly, the Quality Function Deployment (QFD) and the Design Structure Matrix (DSM) have widely been utilized to identify customers' needs and to link them into the created product architecture (Vezzetti et al., 2011).

## 1.2 Research Problem and Objectives

Despite the great efforts within the modeling domain, the majority of methods described in academia typically address the uncommon design situation of an original product development of a single product, where the degree of design freedom remains rather high and solutions can be created independently from current product portfolios and product families. At the same time, studies illustrate that 70-90% of the development tasks are related to redesigning, improving, and extending already existing products (Encanação et al., 1990; Ullman, 1997). Existing design specifications are thereby adapted to satisfy new design objectives and constraints (Fowler, 1996). In addition, product development projects are yet increasingly dealing with rising product complexity (Malmquist, 2002). It has therefore become crucial not only to consider internal relations of the product structure (Eppinger et al., 1994; Lindemann et al., 2009), but also to include a number of different business aspects, such as mass customization strategies (Pine, 1993) and the use of commonality and product platforms (Meyer and Lehnerd, 2011).

To overcome these objections, this research attempts to further develop current modeling methods and techniques, to better meet challenges of designers. By considering up-to-date research and trends, the various aspects of an integrated PD, i.e. activities related to market, product and process are discussed (Andreasen and Hein, 1987). Existing methods are adapted and extended through linking updated requirements to suitable product models, capable of illustrating their effect on both the present engineering solutions and on the physical product and process structure.

# 2 METHODOLOGY

The presented study follows an action research (AR) approach defined by Coughlan & Coughlan (2002). Based on an initial literature review, this paper discusses current challenges and trends of modern PD projects, while particular attention is paid to the established methods and techniques that aim at addressing these challenges. A conceptual model is subsequently proposed, for better integrating upcoming requirements to the product development process. The model is finally tested and verified based on an industrial case. The collaborating partner is a consortium of five Danish

companies and five research institutes, focusing on the development, production, and construction of pre-fabricated High Performance Concrete elements. Even though the organization is profit oriented, like most other companies, it has acknowledged the necessity to do upfront research in related areas in order to move the construction industry forward. Thus a rather innovative product development project has been initiated to create modular building components, that are based on platforms and which correspond to today's requirements. The industrial collaboration is realized through a mixed methods research, in particular through a qualitative dominant research with a sequential time order decision.

### **3 LITERATURE REVIEW**

#### **3.1 Knowledge Representation in Collaborative Product Development**

In today's PD projects there is a growing communication concern to be handled. As a majority of the projects are being performed by working in teams, who frequently work geographically and temporarily independent from each other, related tasks have to be coordinated (Rodriguez and Al-Ashaab, 2004). An important implication of organizing collaborative product development is to be able to answer the question how a design change in redesign will affect the system, either organizational, product or process related (Tang et al, 2010). Traditionally knowledge about partial design solutions relied on the implicit knowledge and experience of individual design engineers (Suh, 2001). To keep up with the competitive environment, it has become important to make relevant knowledge explicit, thus available and shareable to all the parties involved in the development process. Companies which are able to integrate closely the various perspectives of the technical PD together with the required knowledge management will succeed in creating better products in shorter lead times. Product knowledge should represent the product features, their relation to the product components and the way how the created solution meets the marketing strategy. Process knowledge is about the involved business processes, the responsibilities and their interfaces towards supportive technologies. Eventually, project knowledge specifies the resources available, the functional and non-functional requirements, budgets, targets, milestones, and the like (Ebert and De Man, 2008). The implementation of adequate IT systems, such as Product Life Cycle Management (PLM) systems, hereby facilitates the efficient exchange and sharing of relevant knowledge (Vezzetti et al., 2011). The discussed research demonstrates how much modern PD projects rely on adequate and explicit knowledge representation. The following sections investigate how this knowledge is outlined by related modeling methods.

#### **3.2 Methods for Analyzing Product Development and Design Activities**

##### **3.2.1 Requirements Management**

At the heart of any engineering discipline is the interplay between problem and solution domains (Chen et al, 2013). A requirement specifies what the product must do or defines a quality that the product must have (Robertson and Robertson, 2013). Compelling economic arguments justify why an early understanding of stakeholder' requirements lead to systems that better satisfy their expectations (Nuseibeh, 2001). Requirements Management (RM) proposes methods to cope with the requirements at the early phases of the development life-cycle. It presents concepts of identifying, collecting, and allocating "system functions, attributes, interfaces, and verification methods that a system must meet including customer, derived (internal), and specialty engineering needs" (Stevens and Martin, 1995, p.11). On the one hand RM consists of soft processes focusing more on people than products. This characterizes at the requirement elicitation process where requirements are discovered and the main objectives are about understanding stakeholders and discovering needs. When the problem domain is sufficiently well defined, on the other hand harder and more definite modeling techniques can take over (Alexander and Beus-Dukic, 2009). Since detailed descriptions for the requirement specification are typically created in various text based documents of considerable length, it can be difficult to get a sufficient overview of the requirements.

In RM requirements are typically grouped and graded according to their nature, e.g. implied or derived, and the impact the stakeholders have on them (DeFoe, 1993). Investigations on RM challenges have been reported repeatedly over the past years (Juristo et al., 2002). Requirements presentation, as well as incomplete and changing requirements and specifications are thereby seen as a major obstacle that needs to be overcome (Weber and Weisbrod, 2003). The process of moving

between the problem world and the solution world is furthermore still not well recognized. Typically the effectiveness of a solution is determined with respect to a defined problem, however, the nature of the problem and its scope could depend on what solutions already exist or what solutions are plausible and cost-effective (Chen et al., 2013). Recent models suggest that instead of doing RM only at the early phases, requirements definition and design are interactive activities, handled simultaneously though the development life-cycle (Nuseibeh, 2001). RM therefore concerns much more than a list of “shall statements”. Instead in modern approaches RM issues are engineered, involving tools, modeling, database design, customization with scripts, training, and data handling (Alexander and Beus-Dukic, 2009).

### **3.2.2 Matrix-Based Modeling Methods**

Generally speaking, matrix-based modeling techniques help to classify the product structure, i.e. the relationship between elements. Through Quality Function Deployment (QFD) and the Axiomatic Design (AD) method designers can use a series of inter-domain matrixes (Malmquist, 2002) to transfer the requirements (the voice of customer) into specific product attributes, engineering characteristics, possible design solutions and manufacturing activities (Akao, 1990; Suh, 2001). Both methods provide guidelines for designers to make technical decisions more systematically (Hung et al., 2008; Jin and Lu, 1998), with the objective to design customer satisfaction and quality assurance into the product prior to production (Guinta and Traizler, 1993). Successfully implemented, such modeling methods have e.g. helped to increase competitiveness, lower start-up cost, and shorten design cycles (Kovach et al., 2007; Vallhagen, 1996). Further analytical techniques, such as the Design Structure Matrix (DSM) (Steward, 1981), have been developed to assess, reorganize, and cluster relationships between elements (Eppinger et al., 1994). In order to improve the analytical capabilities, the DSM method has since its introduction been further extended, modified, and integrated into other matrix-based approaches, such as the previously described QFD and AD methods (Guenov and Barker, 2005; Hung et al., 2008). From a solely inter-domain matrix with a limited capability of representing the nature of the relationships, over time the DSM method has increasingly been used on various intra-domain problems, namely in form of a Domain Mapping Matrix (DMM) (Browning, 2012), and in combination with fuzzy logic methods (Ko, 2010). Such DSM tools have been used from reorganizing static and time-based relationships (Browning, 2001) to support planning and scheduling activities (Shi and Blomquist, 2012).

In sum, RM methods – combined with matrix-based modeling techniques – are strong in handling the evaluation of customer driven requirements and a vast amount of static and time-based relations. As long as the relations are described on the same level of abstraction and the information flow goes from the customer domain to the process domain (Suh, 2001), the methods obtain powerful analytical qualities. However, the drawback of such techniques is that they hardly support platform design and product redesign (Malmquist, 2002; Simpson et al., 2010), which is, as previously discussed, a prerequisite for today’s product development. The following two sections discuss briefly current approaches within these two domains.

### **3.2.3 Modeling Methods for Platform-Based Product Development**

In mass customization, product specification processes consist of developing the needed specifications to deliver a customer specific product (Hvam et al., 2008). In this area great results have been achieved where customer needs are transformed directly into product designs and production specifications (Pine, 1993). When pursuing mass customization strategies, manufacturers aim at rationalizing their PD through implementing product family architecture based on product platforms (Jiao and Tseng, 1999). In this context, a product platform can be defined as a “set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced” (Meyer and Lehnerd, 2011). Companies implementing platform strategies may among other things reuse parts, assemblies, technologies, concepts, and knowledge while simultaneously reducing unwanted complexity and improving their business potential (Andreasen et al., 2001).

While modeling product family architectures, different phases of the product development have to be integrated with the complying business functions. The formulation of a platform model involves considerations from several perspectives, the so called views. In the functional or customer view, the functionality of the product is first determined. The technical or engineering view then reveals how the

functionality is provided and what technology has been applied. The physical view consequently describes how the product design is realized by the physical components (Jiao et al., 2007). In addition, to be able to access supply chain considerations, a supplementary representation of possible production layouts (production view) is needed (Mortensen et al., 2008). In order to be able to incorporate the different views of a product, generic modeling notations have to be applied that enable the representation of commonality, alternative variety, and ranges (Jiao and Tseng, 1999; Harlou, 2006). Such a generic modeling approach has for instance been pursued by Harlou (2006). The different perspectives and relationships are modeled with the Product Family Master Plan (PFMP) technique, also referred to as a Product Variant Master (PVM) (Mortensen et al., 2000). The method is based on the product architecture definition by Ulrich (1995), the theory of technical systems by Hubka and Eder (1988), and the theory of domains by Andreassen and Hein (1987). Similar to functional modeling (Jiao and Tseng, 1999), by following the basic principles of object oriented modeling, such as generalization, aggregation and association, the PVM technique uses the Unified Modeling Language (UML) standard to create a comprehensive overview of a product architecture (Hvam et al., 2008). With its additional notation, the method shows its advantages in modeling product platform and family architectures.

However, since relationships between elements are mapped only through direct connections (arrows) and constrains (for configuration), when linking all relations of complex products across the different views, the desired overview can no longer be provided. Hence, in the context of relationship handling, the PVM method does not seem to be capable in replacing the strong analytical techniques of a matrix-based model.

### **3.2.4 Product Redesign and Product Line Engineering**

As discussed previously, development projects are rarely original, but are rather based on already existing products and technologies, which can sometimes be a group of similar products or defined as a product family (Smith, 2012). This means that a part of the development artifacts are new and a part of them already exists. For this type of development to be successful, it is therefore essential to be able to reuse as much as possible of the existing artifacts and to understand the relationship between the artifacts in each process step, e.g. requirements, design solutions, tests and processes (Shirley, 1990). Development projects can furthermore be technical, where new innovative solutions are first introduced for general applications and later to be used in actual products. In the case of internal projects, a common objective is to improve existing product structures and design solutions. From this end it is important to understand the upstream traces regarding how new solutions and designs affect the stakeholders (McGrath and McMillan, 2000).

The software society has addressed this issue by methods of Product Line Engineering (PLE) (Rabiser and Dhungana, 2007). In PLE the development process is split into two activities; (1) domain engineering, where the reusable asset is developed and (2) application engineering, where products are developed from the reusable asset in combination with fulfilling new requirements (Pohl et al., 2005). However, also PLE engineering research has reported that further studies are needed in application requirements engineering and in analyzing the relationship between requirements and the solutions (Rabiser and Dhungana, 2007). To facilitate research in RM and PD based on product families, inspired by the development approach of software, as in PLE, the following section introduces an extended modeling method based on the PVM. The method aims at combining the different techniques into one consistent framework and thus to benefit from their individual advantages.

## **4 PRODUCT REQUIREMENTS DEVELOPMENT MODEL**

### **4.1 Introducing the PRD Model**

When assessing the development task of a physical product from a redesign perspective, separately considered, each of the above described methods reveals a strong weakness in providing the essential overview and insight of requirements coming from different stakeholders and their effect on the product architecture. Supportive methods should be able to describe how the customers' requirements are realized, what engineering solutions have to be used, what is the physical structure of the products, and how are these produced. Since it is in particular important to make visual not only which, but also how parts are related, connected or assembled, hierarchical relationships and attributes have to be considered as well. Consequently, the presented Product Requirements Development (PRD) model

builds on the existing capabilities of the PVM technique in mapping the stakeholder's needs to design solutions. Based on an industrial case, the method addresses both, (1) how complex hierarchical relationships can be mapped and (2) how in turn a resulting product design may affect the stakeholders.

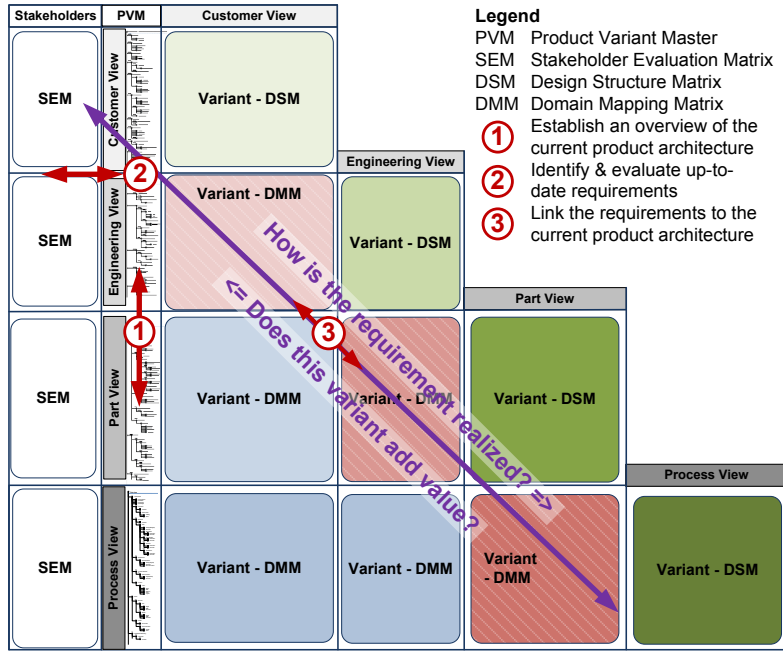


Figure 1 Product Requirements Development Model – Overview

A major difference between the product specification process in mass customization and the development of a new product in a product family is that the first one should fulfill the specific need of a single customer based on available solutions. The latter case needs to consider several stakeholders simultaneously, the impact of new requirements on the product architecture and the effort needed to realize the solutions are unknown. Here, the requirements from each stakeholder have to be evaluated in depth, as they need to be challenged, transformed, and tested by the designers. Since updated requirements have to be set in relation to the current product portfolio, it is eventually inevitable to have suitable models showing the existing product architecture in place. As illustrated in Figure 1, following the notation of the PVM technique, first, if not already available, a generic model of the product family at hand is created. With an additional “Process View”, life cycle considerations related to production, transportation and assembly can be included.

Next, similar to the QFD method, in a second step current stakeholder requirements are identified and directly modeled within the existing hierarchical product architecture of the PVM. As indicated in Figure 1, such requirements can appear in the different perspectives (views) of the model. The most common ones are typically driven by the market and are to be placed within the Customer View of the model. Technology driven requirements on the other hand are mapped in the Engineering View. Besides, requirements coming from other domains can potentially be mapped in the corresponding views. On the left side of the PVM, in the Stakeholder Evaluation Matrixes (SEMs), the requirements are graded and prioritized across the views according to their importance from 1 (low) to 5 (high). The right-hand side of the PVM displays both, the downstream and upstream impact relationships. Complementary to the DSM and DMM technique, the effect of the requirements on other customer attributes, engineering solutions, physical parts, and processes can be mapped through inter-domain (Variant DSM) and intra-domain matrixes (Variant DMM). The difference to the well-known DSM technique hereby is that each side of the matrix is linked to the PVM structure, and therefore allows a concise expression of hierarchies and relationships, e.g. part-of or kind-of structures and attributes

(Hvam et al., 2008). Alternatively, to link hierarchies, variants and attributes with each other using standard matrix-based modeling methods, for each of the seen “Variant DSMs” or “Variant DMMs” a huge number of DSMs or DMMs is needed. Thus in order to obtain the overview of the resulting changes, at this point integrating the PVM technique with the DSM method appears to be beneficial. Having described the principal makeup of the PDM model, in the following paragraph the model will exemplary be applied on the case study.

## 4.2 Applying the PRD Model

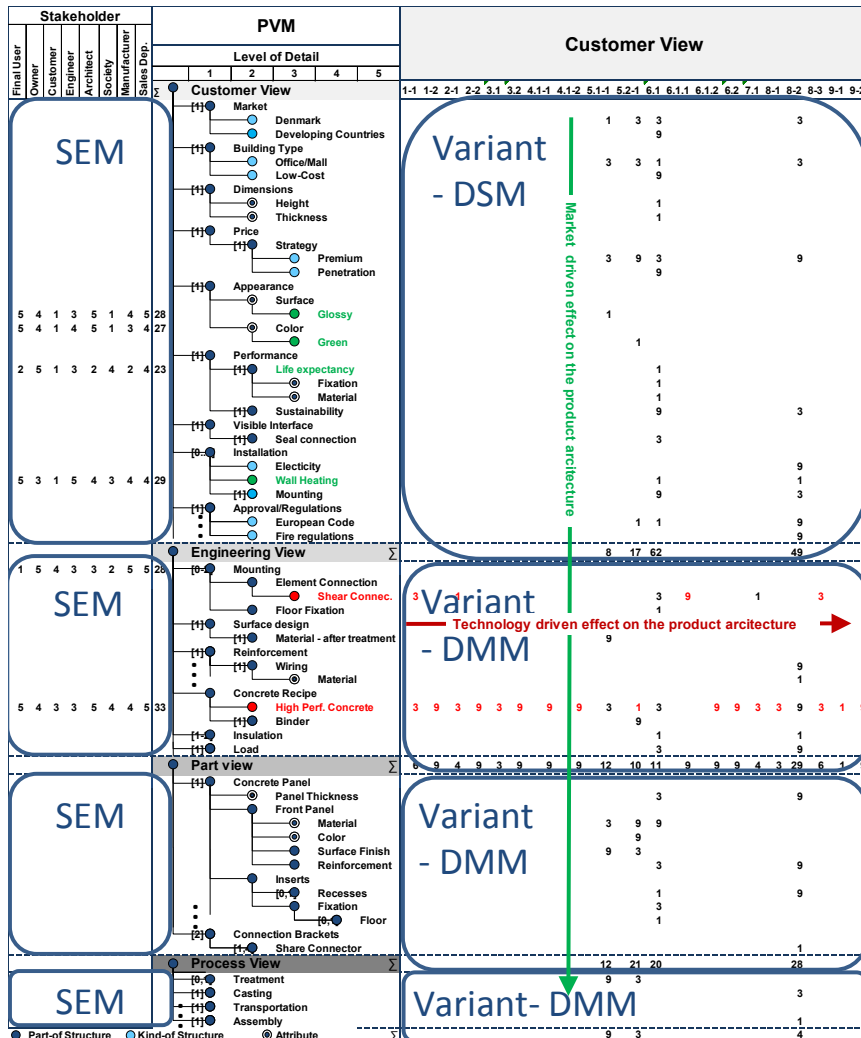


Figure 2 Requirements Evaluation

In the case example first (Step 1) a PVM of high performance concrete sandwich elements has been created. Figure 2 illustrates a small segment of the entire model, where in Step 2 upcoming requirements were modeled directly into the established PVM. Market driven requirements were illustrated in “green” in the Customer View of the PVM. Here they e.g. concern a new surface and color for the concrete panels, as well as a different heating solution. Besides the requirements from the market, in technological development projects, requirements could also be triggered by the used

technical solution as indicated by the “red words” on the engineering level (Engineering View). With the use of the different colors, change requests in the model could quickly be retrieved. Next, on the left-hand side of the PVM the stakeholders of the project were mapped into the described SEMs. In order to formally prioritize their preferences for all new requirements, their individual assessment was aggregated to the sum at the right-hand side of each SEM. Since in the case study all stakeholders had the same relative importance, no other proportional weighting for prioritizing the requirements was needed. It should be noted that in other cases different prioritizing strategies may exist. In some projects stakeholders may either have a greater voting right than others or other rather strategic aspects might be more important. Either way, at the end of this step arising requirements should be given a relative priority.

In Step 3, as illustrated on the right-hand side of the PVM, the impact of the requirements was modeled according to the fuzzy logic model. By grading the strength of the relationships with numbers (1, 3, and 9) (Ko, 2010), again it was possible to formalize how strong the effect of each requirement is on the current product architecture. Rather than only showing if there is a relationship at all, a higher number indicated a stronger effect. Equivalent to the active and passive sum of a matrix (Lindemann et al., 2009), for each Variant DSM or DMM, the total impact of each requirement was calculated at the bottom as the sum of the individual relationships. However, in order to obtain the overview, Figure 2 shows only partly the downstream effects of the requirements. For example, the impact on the stakeholders from the new “High Performance Concrete” (HPC) is depicted through the PVM structure of model. It has both a relatively high priority in the SEM and strongly affects the entire product architecture. “Life expectancy” on the other hand has been less prioritized by the stakeholders. Even though it has a significant effect in the Variant DSM in the Customer View, downstream traces (shown through the Variant DMMs) are less impaired. Another example shows how even more detailed requirements, such as the new “shear connection” can directly be shown within the model. Since “shear connection” is a part-of the mounting group, its indirect effect on a higher level of detail can be seen. In relation to the other requirements, it had a moderate priority from the stakeholders. But since it is not directly visible to the end users and affects a rather limited number of physical components, its impact on the remaining architecture is narrowed. All in all, by integrating the different modeling methods, this method shows how requirements have been graded by the stakeholders (upstream effects) and how they in turn affect the product architecture (downstream effects).

## 5 CONCLUSION AND FURTHER WORK

Product models, capable of representing how updated customer requirements affect the product lifecycle, enable designers to preserve the overview of the current product architecture, to better coordinate upcoming development activities, and moreover to plan and to calculate alternative solutions. By making use of established product modeling methods, such as the UML-based PVM, this paper contributes to an integrated PD process, which aims at better responding to the requirements of modern product development. Through the integration of several modeling techniques, the presented PRD model overcomes some of their individual drawbacks, e.g. the representation of hierarchical levels, product variants and attributes, while still being able to visualize correlations. Therefore, with the right integration, the PRD model expands the individual modeling possibilities. In sum, it (1) enables the representation of complex hierarchical relationships in a generic product model, (2) links and evaluates updated requirements to several levels of the product architecture, and (3) illustrates how these requirements have an upstream (towards stakeholders) and downstream (towards production) effect on the product architecture. However, in order to address all subsequent aspects of the PD process and therewith to explore the full potential of the model, further research needs to be done. It would for instance be interesting to investigate how matrix-based analysis methods, such as partitioning, could be solved with the Variant-DSMs and – DMMs of the model. Here, future research could for instance focus on what impact structural improvement of the product, through e.g. modularization, could have on the entire product architecture as well as on new requirements.

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## APPENDIX J

# Supporting the design and mass customization of product family architectures using computational structural analysis methods

**Authors:** Martin Bonev, Lars Hvam

## 1 Introduction

A growing demand towards higher product variety and customization has been reported in many industries (Funke and Ruhwedel, 2001; Klenow and Bills, 2001). Acting upon this trend, companies aim at obtaining higher customer value and stronger economic benefits through rapidly responding to individual needs for customization. Product customization describes the process of configuring a valid design by selecting feasible compositions of somewhat predesigned components within a predetermined scope of the offered variety (ElMaraghy et al., 2013). Its individual significance may have multitude reasons, including individual preferences, regional requirements, social values or specific application environments. However, high and diverse product mixes are not always beneficial. Manufacturers offering large product variety are often challenged with a related increase in operational complexity which drastically decreases their efficiency in sales, design, production and distribution (Åhlström and Westbrook, 1999; Blecker and Abdelkafi, 2006). Several approaches have been proposed to address this trade-off, including knowledge-based engineering, flexible manufacturing, form postponement and product modularity (Meredith and Akinc, 2007; Rodriguez and Al-Ashaab, 2005; Rudberg and Wikner, 2004).

Platforms and modules built into product family architectures have been reported to facilitate working with diverse product variants (AlGeddawy and ElMaraghy, 2013). In this context, architectures are described as an abstract structural representation of the functional units and the corresponding physical components of engineering artefacts (Ulrich, 1995). Their development is complex and long lasting and their performance can have wide-ranging effects on the success of manufacturers (Yassine and Wissmann, 2007). The design of architectures suitable for customization raises additional difficulties to organizations, since the right product composition and part compatibility needs to be ensured. Product configuration systems have been developed by software vendors to handle this demanding requirements for information processing, storage and retrieval of feasible variant combinations (Trentin et al., 2011). Configuration systems or configurators are software-based expert systems that capture the generic architecture of product families in a computer model, through which users are supported in creating feasible product solutions with a minimum number of choices (Hvam et al., 2011). Combined with well-designed product family architectures, companies utilize product configurators to mass customize their offerings, i.e. to automate operational activities related to product customization and to increase their efficiency to a level which is close to mass production (Jiao et al., 1998).

However, it can be difficult to identify good product family architectures during product design and to sustain their subsequent implementation in a configuration system, since they are qualitative and supporting methods during development and verification are limited (Li et al., 2011). At the same time, configuration software vendors are of no help in this respect, as they are typically not interested in providing a transparent and easy way to create and communicate product family architectures, but rather emphasize consulting services around the modelling and maintenance of product families (Forza and Salvador, 2008). Hence, with the development progress of product families, software experts have problems in keeping an overview of what had been implemented in the computer model and verifying the obtained architectures with domain experts, making it one of the main reasons why designing and mass customizing products is still difficult to achieve (Haug et al., 2012).

To address this issue, this paper proposes a computer-assisted approach which allows domain experts to document, communicate and design entire product family architectures build into configuration systems more effectively. The approach is complemented with a case study of a major plant and machinery provider of highly customizable products to develop a concrete method on a real world problem. The method combines the capabilities of a state-of-the-art configuration software with automatically generated grammar graphs representing the implemented architectures. The graphs are modelled with an integrated design model (IDM), using the suggested extended modelling techniques for generic structures. The IDM tool is further employed to assist domain experts in synthesising feasible architectures and to computationally evaluate their structural characteristics through a series of metrics, potentially leading to better solutions. The obtained results indicate that the method has value for industrial praxis. The remaining part of the paper is organized as follows. Section 2 provides background on the major concepts for mass customization relevant to the context of in this paper. Formal and informal methods for product family design are discussed in Section 3, and requirements for a support method are identified. Next, existing modelling techniques facilitating such a method are extended to meet the discussed requirements. Section 4 demonstrates the support method on the industrial case and Section 5 concludes with the advantages and limitations of the proposed approach.

## **2 Enablers of mass customization**

The aim of mass customization is to increase the compatibility between customization and responsiveness, i.e. to enable a rapid development, production and delivery of customizable products. While the basic concept can be traced back to the late 1980s (Davis, 1987), a major challenge of this paradigm is to establish the right internal capabilities, which would allow companies to reach a large number of customers as in mass markets with the additional value of tailoring products to specific needs. Apart from adjusting manufacturing processes (Squire et al., 2009), in this context, the two other major concepts frequently named in literature will briefly be discussed.

### *2.1 From product design to product family design*

First, handling and designing different products variants for customization is a costly and long-term process that includes unforeseen risks and uncertainties. It is typically not feasible for manufacturers to develop individual architectures for each niche market. Instead, product design, planning and production needs to shift focus from mastering individual products towards developing additional features at decreasing costs (Simpson, 2006). The planning for variants is facilitated through the grouping and classification of similar functionalities and components into product families. The architecture of a family defines how the functional units are related to the physical elements and the way in which these elements interact to create the desired product variants (Wie et al., 2007). A common objective hereby is to capitalize on increased reuse of common elements across different products, without reducing the distinctiveness of features critical for the market performance (EIMaraghy et al., 2013). However, in variant-oriented design changing and adding elements within the architecture may have a strong impact on primary parts and functionalities. To reduce the risk for malfunction or part incompatibility, it is important for designers to understand the reconfiguration of an existing family design and to develop of compatible elements with preferably little impact on the remaining architecture (Alizon et al., 2007). Hence, the design of this so-called modular architecture is often employed to create of derivatives with different functionality and form, whilst obtaining economies of scale through a high level of communality between variants (EIMaraghy, 2005).

### *2.2 Employing configuration systems for customization*

Furthermore, to effectively address a wider range of customers with the experience of an individual value creation, additional key technologies have to be employed. Customer-driven design relies on the

systematic reuse of architectures that meet individual demands with configurations which are feasible in functionality and which fulfil the limitations of manufacturing. The progress of computer technology and artificial intelligence in the late 1990s made it possible for manufacturers to employ expert systems which are specifically designed to integrate the design space into sales processes as a reuse strategy. Once implemented as a computer model, product family architectures represent the knowledge base of model-based configuration systems. With their help individual preferences are translated into correct and complete specifications during order acquisition and fulfilment, such as product details, price lists, bills of material, manufacturing instructions etc. (Forza and Salvador, 2002). Due to their functionality, today product configurators are one of the most successful applications in artificial intelligence systems and can increasingly be found in the majority of industries (Felfernig et al., 2004; Stumptner, 1997; Tiihonen et al., 1996). Modern applications employ generic product architectures and sophisticated interference engines with search algorithms from operations research to display the exact propagation of design changes. Besides they apply visual and interactive representations (dynamic and static) to guide users through the process of making valid solutions (Hvam and Ladeby, 2007).

Nevertheless, access to state of the art expert systems in academia is rare and restricted and often limits the progress of research within this area. In result, advancements in configurator technology are seldom being adopted by engineering domains, thereby increasing the risk of a frequent reinterpretation of existing best practises (Jiao and Helander, 2006), or for the redefinition of well-understood capabilities for mass customization (Helo et al., 2010). Another common misinterpretation of configurators may come through term itself. Product configuration as such is often confined to the process of recombining existing building blocks of a modular product architecture (Jiao et al., 2007). Therefore, for many researchers and practitioners employing configuration software means to develop simple marketing tools, i.e. advanced (online) product catalogues with a fixed set of predefined and often static components, which can gradually filter out possible solutions (Brière-Côté et al., 2010). Hence, without further insight, the capability configuration systems is reduced to assist this elementary filtering process, thereby ignoring two important aspects. First, modern model-based systems are able to employ a knowledge base of determinant or parametric elements which may cover a complex solution space tending to infinity (Felfernig et al., 2012). And second, configurators may alone or in combination with one or more supportive IT systems, e.g. computer aided design (CAD) or engineering calculation software, be used to assist design departments in solving a variety of customization and design automation problems (Orsvärn and Bennick, 2014). In fact, unlike often reported (Salvador et al., 2009), in praxis configurators are mainly implemented internally to partly automate the customization of industrial engineer-to-order products (Haug et al., 2011). To avoid this misconception of the software's capabilities, this paper understands configurators as computer-based expert systems which use generic product family architectures to efficiently assist enterprises in their customization process.

### **3 Designing and mass customizing product family architectures**

#### *3.1 Approaches in architecture design*

The design of architectures and their subsequent implementation in configurators involves domain experts from different departments and often physically disconnected teams. On an overall level, companies need to create customizable product families, implement their architecture in a computer model, communicate and maintain the architectures and promote their functionalities to the market. Several researchers have acknowledged the related organizational challenges in architecture design and have proposed methods on how to arrange corresponding activities in a more systematic manner (Ardissono et al., 2003; Forza et al., 1994; Hvam et al., 2004). In engineering domains Pahl et al. (2006) address architecture design on several stages, from formulating customer needs to the construction of embodiment and detailed design (Pahl and Beitz, 1996). Corresponding to these different phases of development, Jiao et al. (1999) argue for an architecture modelling framework which in addition

considers several views of a product (Jiao and Tseng, 1999). Yet other researchers promote a top-down strategy of the design process, which aims to connect customer requirements to scalable architectures based on platforms and modules (Meyer and Lehnerd, 1997; Simpson et al., 2001). At the same time frameworks dealing with architecture design for expert systems typically fall within the area of software systems and base their methods on the life-cycle of object-oriented software development as introduced by Booch (1986). Booch's object-oriented procedure was originally developed to handle the complexity of large software projects by breaking down the development work into phases of object-oriented analysis, design, implementation and maintenance (Booch, 1986). To enable the representation of a large number of physical artefacts with components and variant combinations, related frameworks commonly build upon methods for modelling software architectures using the unified modelling language (UML) (Felfernig et al., 2000).

Although the UML standard proved to be particularly useful for defining entire product families, its application within engineering management remains limited. In consequence, synergies on coinciding aspects of architecture design are seldom being achieved. For example, the challenge of modelling different architecture views has been repeatedly addressed within the two domains and has resulted in comparable outcome (Brière-Côté et al., 2010; Haug et al., 2010; Jiao and Tseng, 1999). Moreover, advancements within engineering management are seldom adopted to software design and vice versa, in particular with regard to the formal computational management of structural properties in complex architectures (Lindemann et al., 2009). And second, the development of a product family architecture for expert systems is often organized within IT and product data management departments. The process is regarded as a liberally new modelling approach which is detached from any preceding design activities of the product development phase (Speel et al., 2001). This means that in praxis the design of architectures is not coordinated across the organization, leading to computer models which are very likely to differ from the original design intent of the engineers (Haug et al., 2012). Especially for more complex products, this lack of consistency increases the risk for providing undesired product variety to the market. As a benchmark report with more than 300 manufacturers of custom tailored products reveals, the top performing companies with engineering intensive portfolios try to overcome this coordination burden by better involving development engineers into the architecture design process for their configuration systems (Aberdeen, 2008). This suggests that a more integrated approach to mass customization is needed, which equally considers both the architecture design process and the subsequent implementation into configuration systems.

### 3.2 Informal and formal architecture design strategies

Fig. 1 displays how the architecture design process may be realized in a consistent framework. The focus of this paper is indicated by the grey area in the model and combines design aspects from engineering and software domain. The procedure is initiated by a design problem and ends with a customized solution created by the user of a configuration system. As indicated in the model, supporting methods can be informal, relying on subjective interpretations of domain experts, or formal, involving codable and systematic procedures. Widely used informal methods depend on human creativity and may include simple brainstorming principles (Osborn, 1963), and more guided brainwriting concepts (Heslin, 2009). However, architectures can be created in many different ways. The qualitative character of the design space makes it difficult for domain experts to develop new architectures, or even to be able to consider alternative solutions for a product family (Wyatt et al., 2011). If lacking a systematic guidance, domain experts often base their work on experiences from previous design problems. When a new design task occurs, they tend to commit early to familiar solutions which may be premature and not well suited for the underlying problem. This so called fixation effect restricts practitioners from constructing previously unknown yet potentially better solutions (Purcell and Gero, 1996). In the same way, fixation has a detrimental impact on the quality of the architecture in the computer model. To guide

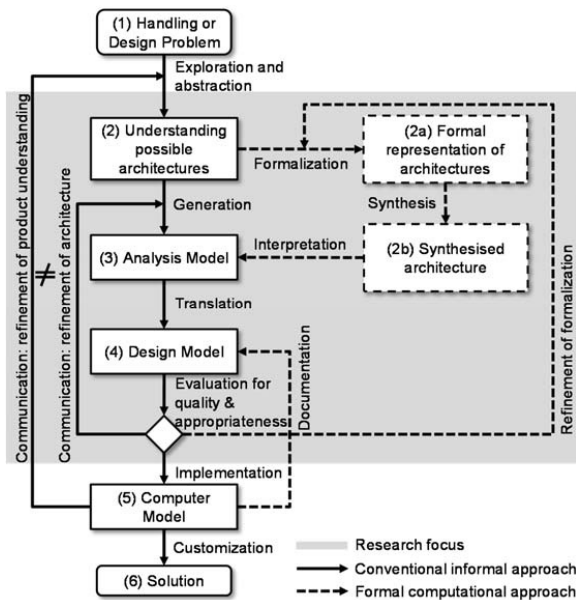
developers in creating new models, modern configurators contain knowledge base editors and supportive debugging methods (Liao, 2005). They assist software experts in constructing executable computer models within the software environment, but fail to abstract, document and represent the product architecture so that it can be retrieved and communicated effectively (Li et al., 2011). Hence, configurator experts have little or no possibility to collaborate with domain experts when developing computer models, which additively reinforces the fixation problem. Moreover, they have to go through architecture models with potentially thousands of elements within the configurator and manually compare them with the previously developed architectures without being able to adequately abstract the underlying design problem.

In contrast, as the complexity of the designs increases, formal approaches are becoming increasingly important. In complex design problems they are often based on computational models which are used to synthesize potential architectures (Cagan et al., 2005). In order to evaluate a solution based on a formal synthesis the architecture problem has to be made explicit, thereby providing a transparent and more reliable form of reasoning. In addition, proper documentation and knowledge representation methods may enable an intuitive comparison of architectures and hence increase the reliability of the expert system (Verhagen et al., 2012). The two alternative approaches may be organized along a five phase model of exploration, generation, evaluation, implementation and communication, which is based on the established development model of design science (Cross, 2008). Inspired by Wyatt et al.'s (2011) architecture design framework, the process can be described as follows:

- *Exploration* helps engineers to examine the handling of existing design or the work on a new design problem. Typically, product information can exist in many different formats, such as diagrams, tables, formulas, computer aided design (CAD) files, bill of materials (BOMs) etc. Different departments within a company may even have their own representations of products. By *abstracting* the relevant product information (1), engineers develop an understanding of possible architectures (2).
- Based on a created understanding of possible architectures, engineers *generate* a specific family architecture in form of an analysis model, which may be the same as previous solutions and further contain errors (3). Discussions on the product architecture during the object-oriented analysis may involve various domain experts coming from product design to sales and marketing. Since not all departments are necessary familiar to the same technical detail of a product, often this is done by visually representing the product family in graphical models and describing the combinatorial possibilities in a way which is similar to the natural language. For instance, using pseudo-code for constraints instead of mathematic expressions, in form of 'component A has to be as wide as component B', makes the models more appropriate for a cross-disciplinary communication.
- The analysis model has to be *translated* into a design model (4), which is more suitable for the subsequent *implementation* into a computer model (5). The aim of this step is to adjust the representation language of the analysis model into a format which is common to the one of the final computer model of the configurator. Rules describing the combinatorial feasibility and solution principles of a product family have to be expressed in mathematical equations, making them readable and understandable by the software. In addition, the product family architecture may be extended with information related to the configurator design, such as the user interface, details on the implemented methods or the interaction with other IT systems. Depending on the experience of the project stakeholders, in praxis this step may not be strictly separated from creating the analysis model, but often involves further detailing of the architecture.
- The design model is *evaluated for quality and appropriateness* to determine whether the created solution fulfils the problem at hand at the best possible way. Has the architecture been accepted, the design model can be *implemented* as a computer model (5) in the configuration system. If not, the architecture is *communicated* to the design team, to iteratively *refine the solution*.



- Users (internal or external) of the configuration system can *customize* their solution based on the implemented computer model. If the offered solution space is either faulty (wrong configuration) or does not reflect the desired variety (missing or unwanted configuration), the computer model may be *communicated to refine the understanding* of the problem. Though both aspects are critical for the acceptance of the configurator, the latter becomes particularly important in markets where demands are frequently changing and enterprises need to keep pace with these changes. As with this approach, no mechanism is typically established to ensure the constancy between design and computer model, the two communication processes illustrated in Fig. 1 do not necessary represent the same product architecture and are thus to be considered separately.



**Fig.1: A consistent model for designing and mass customizing product family architectures based on informal and formal methods (after Wyatt et al., 2011)**

As discussed above, the generation and implementation phase of the informal approach may be critical for the quality of the obtained architecture. The dashed lines in Fig. 1 illustrate how this can be avoided by a formal computational solution:

- The understanding of the possible architectures (2) can be *formalized* through a guided modelling environment and the representation of alternative architectures (2a).
- The computational methods assist domain experts in *synthesizing* a possible architecture (2b), which is then *interpreted* as an analysis model (3), and further translated into a design model (4). If the solution does not meet the evaluation requirements of the underlying problem, the development team may iteratively *refine the formalization*.
- Has the design model been accepted, it may be *implemented* as a computer model (5). To ensure the consistency between computer and design model, it needs to be *documented* and compared against the design model. *Communication* helps to refine the architecture and/or the product understanding, which may be internal (towards the development team) or external (towards

customers). Since product architectures are typically developed iteratively over time, for large and interconnected models proper documentation and communication becomes particularly important. In such cases the documentation and communication of already developed implemented architectures is a prerequisite for any further development.

### 3.3 *Requirements for a formal architecture synthesis*

The majority of methods for formal architecture design synthesis are based on engineering management literature (Chakrabarti et al., 2011). They vary from numerical optimization approaches of partial design problems for single products (Ziv-Av and Reich, 2005), through heuristics for module optimization in product families (Jiao et al., 2008), to morphological analysis methods for incremental design improvements (Kurtoglu and Campbell, 2009). Methods considering entire products are often based on ontologies, i.e. grammars applied to graphs to display architectures (Schmidt and Cagan, 1997). A widely used technique for such graphs is to map architectures through their structure with nodes and links, i.e. to create an abstract representation of the underlying elements identified by their type and relations (Andreasen et al., 1995). The so called node-link diagrams express objects (components or functions) of the product and the edges stand for the connections or interfaces between them. The product architecture may be modified either through changing the structure of the model, i.e. by redefining the connections between elements, or through altering the objects as such. The latter may for example mean to add new components and/or functionalities to a product. Adjacency matrices provide an alternative well-organized and compact representation of elements and their relationships. As one of the first supporters of this modelling method, Steward (1981) applied adjacency matrixes also known as design structure matrices (DSMs) to display elements and their relationships (Steward, 1981). Based on his work, a number of additional (computational) matrix-based techniques have been proposed over the years (Eppinger and Browning, 2012). These two simplified grammar graphs can be used to create entire new architectures or to evolve existing ones. This is particularly useful, since architecture design is typically incremental, where products are upgraded over time and their components are reused in alternative or later products (Clarkson et al., 2004). Examples for computational design synthesis using structural grammar graphs can e.g. be found in (Lindemann et al., 2009; Wynn et al., 2010).

Research dealing with configuration systems has likewise recognised the need for a formal architecture design and implementation approach, where for example the handling of complex highly connected models has been addressed explicitly (Tiihonen et al., 1996; Wielinga and Schreiber, 1997). In particular the challenge of documenting and communicating entire product family architectures has been discussed in several studies (Haug et al., 2010; Hvam et al., 2005). The authors conclude that the complexity of the models makes it infeasible to update and visualize each model manually without any guidance, but requires dedicated methods and software tools. At the same time, comparable computer-based design synthesis methods as suggested for single product design are yet missing. Important contributions of informal approaches to be mentioned in this context include the product family architecture (PFA) approach (Jiao et al., 1998), the use of class diagrams and CRC cards (Aldanondo et al., 2000), the frames parts components (FPC) model (Magro and Torasso, 2003), and the product variant master (PVM) (Hvam et al., 2005). The majority of the so called generic methods use variations of object-oriented modelling based on the UML standard to describe hierarchical composition of elements (generic part-of-structure), their possible variants (kind-of-structure), and their combinatorial interfaces to other elements (collaborations) (Felfernig et al., 2000). The UML notation includes the object constraint language (OCL) as an expression language of how elements in a model are combined with each other. Due to their additional notation, generic methods can be regarded as an extension to the structural representation of the grammar graphs discussed above. Further details about the slight differences of the methods can e.g. be found in (Hvam et al., 2014).

Despite the advantages of computational synthesis methods, their application in industry has been limited. This may be partly explained by to the mismatch between the needs for such methods in architecture design praxis and the systems developed hitherto. To overcome this, related studies have recently proposed general requirements that address the described aspects of formalization, synthesis, interpretation and refinement for single architecture design (Wyatt et al., 2011). Since the design process is typically incremental, a formal method should guide engineers to specify initial architectures as a starting point for synthesizing new solutions. The corresponding design problems may then be decomposed into smaller interlinked sub problems, represented by the relevant model elements, while the possible solution space should be declared explicitly through constraints. For instance, architectures representing the energy consumption of diverse production plants might not necessarily include all elementary machine elements, but rather consider major factors (components and properties) and their ranges influencing this value. Next, synthesized architectures should be presented and evaluated through their structural features which have favourable or unfavourable effect on any lifecycle objectives of the product family. Frequently used metrics for example investigate the commonality and modularity of different architectures (Sosa et al., 2007). The problem formalization may then be refined by the engineers as a consequence of their interpretation of the synthesized solution. The obtained architecture is documented to ensure its consistency throughout development and implementation, and is communicated to modify the understanding of the problem. For instance, new production lines might need to be added to an implemented model of a plant, for which the already created architecture would be required.

Category	Requirement	Content
Formalization	F1 Incremental design	Guided architecture creation as a starting point for synthesis
	F2 Problem decomposition	Abstract sections and focus on relevant scope
	F3 Problem-specific architecture	Represent relevant elements in ways that fit the problem
	F4 Declarative evaluation	Declarative constraint-based representation of the solution space
Interpretation	I1 Interpretation support	Present synthesised architecture and allow for further evaluation
	I2 Feature-based evaluation	Specify structural features according to lifecycle objectives
Refinement	R1 Refinement of formalization	Support modification of the problem formalization
Documentation	D1 Consistent architecture design	Ensure architecture consistency throughout design and implementation
Communication	C1 Complete and correct representation	Consider graphically all structural aspects of product families

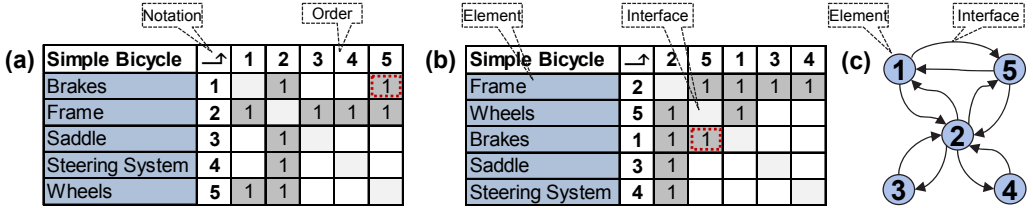
Table 1 summarizes the requirements a for computational design synthesis as proposed by Wyatt et al. (2011) and complements those with the context specific aspects of *documentation* and *communication* of product families. Since the described recommendations and the underlying graphical methods are reduced to the special case of designing single product architectures, they have to be tailored to the context of this paper. The most profound aspect arguably addresses the ability to model, synthesize and communicate entire product family architectures using the discussed graphical grammar approach. To obtain a deeper understanding for a supportive method, the next section uses an illustrative modelling example to briefly address the limitations of the existing grammar graphs.

### 3.4 Modelling product family architectures

#### 3.4.1 Adjacency matrices

In accordance with the definition in Sect. 2.1, architectures are modelled as abstract description of the entities of a system and their relationships between each other. The DSM format is employed to display relationships of such entities (functions or components) of the same type for single products. Each element is represented by a row and a column, while entries in the DSM indicate a link from one node of the matrix to the other. Two different conventions exist in literature to describe the direction of a link.

The IR/FAD convention uses element inputs shown in rows and outputs in columns. The IC/FBD convention of the other hand shows element inputs in columns and outputs in rows. The two notations are based on the same information, where one is the matrix transpose of the other (Eppinger and Browning, 2012). To illustrate the functionality of the DSM method, we use the letter notation in a simplified modelling example of a bicycle provider. As model (a) in Fig. 1 shows, our bicycle consists of five main components. All elements have been ordered alphabetically and their interfaces to each other are shown through the entities of the DSM. In this way the product structure consists of interconnected components shown as a squared intra-domain matrix. Alternatively, to represent the structure of two different domains within the matrix, e.g. components and functions, the additional domain may be listed on the other axis. This variation of the DSM is also called domain mapping matrix (DMM) and is based on the same modelling notation as the DSM. The DSM layout requires product elements to be listed strictly on the horizontal and vertical axes, making it a rather rigid but at the same time very compact and scalable way of describing structures of single products (Abuthawabeh et al., 2013). This well-defined arrangement has proved to be particular useful for computational analysis methods. For example, a very popular way to identify potential modules is to cluster the links between elements in chunks. This method is illustrated in model (b) of Fig. 2. The order numbers in the DSM indicate how the elements have been rearranged compared to the alphabetical order to form a potential module.



**Fig.2: Different analysis models of a hypothetical bicycle, (a) DSM (alphabetical order), (b) DSM (clustered), and (c) a node-link diagram**

### 3.4.2 Node-link diagrams

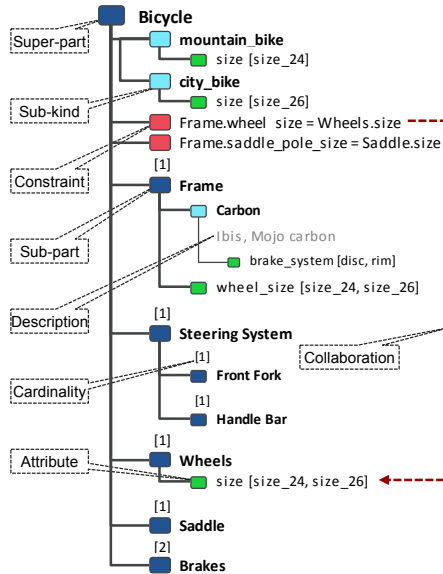
Node-link diagrams offer an alternative increasingly popular graphical representation of product structures, as described in Sect. 3.2. Initially such graphs widely been used in social network analysis studies with the purpose of characterizing the nature of social relationships among a set of actors (Freeman, 2004). Each actor within a given network is represented in a node and arrows between the nodes stand for links between them. To display their relationships, the nodes of a model can be placed freely within the entire two-dimensional space, making this type of graph very flexible in layout. Especially for large models with many nodes, this flexibility can be very convenient. Model (c) in Fig. 2 illustrates our bicycle example in form of a standard node-link diagram. As indicated by the layout, the frame is central for the entire structure of the model. It provides input to all remaining components and at the same time is connected through the same amount of interfaces from them. Depending on the actual analysis problem, a rearrangement of the graph allows the user to visually access only relevant network area, leaving out less important aspects unconsidered. Additional colour and distance coding may help to display social clusters and the strength of individual relationships. An extensive study on algorithms for drawing node-link graphs can for example be found in (Battista et al., 1994).

### 3.4.3 Generic product models

Fig. 3 displays an example of the bicycle model expressed in the PVM notation introduced in Sect. 3.3. Similar to assembly models in computer aided design (CAD) systems, the model imitates the aggregation of elements through a hierarchical list connected with lines. The different colour codes

represent the element type and the letter size indicates the corresponding hierarchy level. In general there are four different element types in a model: *parts* (functions or components), *kinds* (variants), *attributes* (properties), and *constraints* (rules). Each part and kind element stands for an *object* or *class* in the model. As an example, a wheel is an object in the model and a different wheel type is modelled as a separate object. The character of an object can be explained by attributes and constraints. *Attributes* are defining the properties of an element, i.e. length or with of a wheel, while the constraints are specifying how these properties operate within the product. An important difference between *parts* and *kinds* is that parts can have both sub-parts and sub-kinds, while kinds may only include other sub-kinds, e.g. a van may be a family van or a transporter. The *cardinality* of parts is indicated by an index above each part. It defines how many times a particular component is to be found in the model and whether this component is optional ( $0..n$ ) or mandatory ( $1..n$ ). To illustrate the representation of hierarchies and variants, further details have been added to the bicycle model. The steering system of the bicycle can for example be described as the *aggregation* of a front fork and a handle bar. If viewed separately, each of the two components has an individual set of *attributes* and *constraints*. For example, the front fork has a clamp diameter that needs to fit with the wheels and the handle bar requires a certain type of brake system. Only in combination however, they create the required functionality for steering. As shown with the DSM technique, without this part-of structure we would have to decide which level to focus on at the first place, leaving out many other essential aspects unrevealed.

The principle of constraints can be illustrated on two additional examples which have been included on the top level within the model. In accordance with the requirements for a design model in Sect. 3.2, the constraints use attributes with mathematical equations to specify the geometrical relationship between the frame, the wheels and the saddle. Another important feature of such object-based models is the concept of *inheritance* and *encapsulation*. *Inheritance* means that the sub-kinds of elements inherit the generic properties of the super-element. For example, all bicycles in have consist of the same major components shown in Model (c). A mountain bike however may have a particular wheel size. *Encapsulation* on the other hand restricts objects at the same hierarchy from interfering with each other's properties. This means that a relationship between two components from the same hierarchy can only be expressed by constraints on the parent object. In this case, the bicycle frame has to fit with the wheels and the pole size of the saddle has to fit with the equivalent size of the frame, which has to be listed directly under the super-part of the model, as indicated by the dashed arrows in Model (c). In object-oriented modelling these interfaces are referred to as *collaboration* or *association* between two objects. In accordance with the common modelling environment of modern model-based expert systems (Acatec, 2014; Oracle, 2014; Tacton Systems, 2014), typically the PVM notation provides no standard visual representation for such a connection. Hence, because all interfaces between components are expressed through constraints, the generic approach alone proved to be disadvantageous when it comes to documenting and analysing the structural properties of product architectures (Bodein et al., 2014). As studies within the automotive industry show, especially for complex products designers and software engineers found it difficult to identify the relevant relationships among product elements, which creates additional challenges for changing and verifying existing architectures (Salehi and McMahon, 2011). Moreover, the extended syntax of the generic methods requires some experience in creating valid architectures. Modelling mistakes can easily occur if no systematic guidance through dedicated modelling tools is provided, which however are missing to date. In result, incorrect generic models can sometimes even be observed on examples provided by literature, where for instance inheritance has been ignored (Haug et al., 2010).



**Fig. 3: PVM example of a hypothetical bicycle family.**

### 3.5 Evaluation and extension of architecture design methods

It is notable that when considered separately, many of the requirements in Sect. 3.3 cannot be fulfilled with of the modelling methods discussed above, in particular:

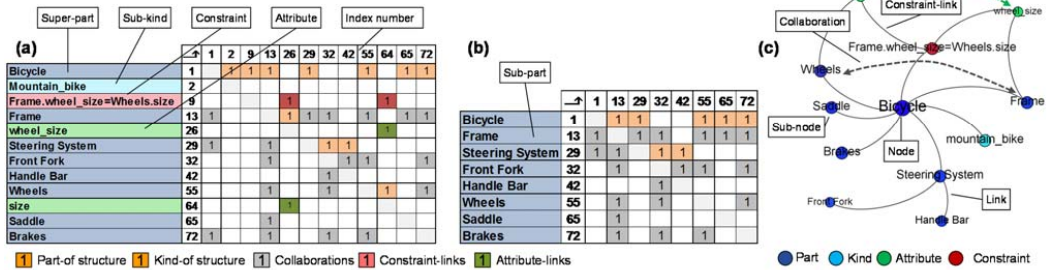
- Grammar-based methods are by definition procedural and qualitative and need to be supplemented with metrics to obtain a descriptive explanation of the design problem (Requirement F4). Yet existing methods apply only for single products (Lindemann et al., 2009), giving the need to develop new methods and formalization procedures (Requirement F1).
- While several clustering algorithms exist in literature (Steward, 1981), our simple example also shows the limitations of such a method. Despite the small number of major elements, the components of a bicycle are connected in ways which do not allow a creation on any obvious modules. This limitation is often compensated by emphasizing on the visual display of structures (Requirement F2). Here, matrix-based representations have proved to be more suitable for most of the tasks in large and dense graphs (Ghoniem et al., 2005), which are very likely in the context of this study. Due to their rather restricted yet scalable layout, DSMs are applicable for products consisting of many interconnected components. As the layout of node-link diagrams is less prescribed, in complex product structures nodes and edges tend to overlap in ambiguous ways, making it challenging to navigate through the network and to identify patterns. However, if used properly in a dedicated software, a network representation with nodes and links is still more intuitive graphical representation and better suited with respect to finding paths between two nodes (Keller et al., 2006) (Requirement F3). Nevertheless, the two methods do not consider any representation of hierarchical compositions or variants, making them being too simplistic and impractical for modelling product families or any form of customization (Requirement C1) (Keller et al., 2006; Malmqvist, 2002).
- The discussed grammar graphs as such do not provide any information about the nature of the identified interfaces. To obtain more detailed understanding about the product features and its links,

additional external metrics are needed (Requirement I2). This may be partly overcome with the extended notation of the generic models, such as the PVM. However, these models do not visually represent interfaces (collaborations) between components (Requirement F2), but rather use mathematical equations to express such through constraints (Requirement C1). Furthermore, the extended modelling notation requires additional guidance to obtain correct architectures (Requirement F1).

- Documentation is not explicitly supported by the existing methods but requires additional methods for that, increasing the risk for obtaining an inconsistent architecture design (Requirement D1).

The evaluation of the methods suggests that many of the requirements can be addressed explicitly by extending the existing notation of the relatively simple grammar based approach of DSMs and node-link diagrams. Especially Requirement F2, I2 and C1 can be directly met with a modelling technique which includes aspects of the generic grammar but which also provides a complete graphical representation of structures. Fig 4 presents how such an extension may be realized and corresponds to the common perception that multiple views of an architecture help to better understand the underlying design problem (Keller et al., 2005) (Requirement F3). The so called integrated design model (IDM) combines the different functionalities of DSM, node-link graphs and PVM into a consistent representation form. Model (a) in Fig. 4 shows the generic structure of the bicycle into a matrix format (generic DSM). In addition to the main components from Fig. 2, rows and columns in the model may include sub-parts, kinds, constraints and attributes. Entries in the matrix are used to express existing interfaces for part-of structures, kind-of-structures and collaborations. The scalable layout of a DSM further allows to consider two additional types of interfaces. *Constraint-links* define which attributes are being used in this particular constraint, while *attribute-links* display the connection between these attributes. Accordingly, collaborations exist whenever there are constraints causing an interface between two objects. It is worth noting that interfaces caused by constraints are by definition symmetrical, which in our example means that both frame and wheels have to fit to each other. Hence, entries for attribute-links and collaborations appear on both sides of the matrix diagonal.

The extended notation of the generic DSM enables users to *abstract* the underlying architecture design problem (Requirement F2), which may be done by: (1) changing the *level of detail*, i.e. connections represent the architecture at any level of granularity, and (2) changing the *scope*, i.e. to focus on a particular set of elements, without altering the remaining architecture. The principle of abstraction can be demonstrated by comparing Model (a) and (b) in Fig. 4. While the first model is to some extent showing a higher level of detail of the entire model, Model (b) displays the same generic architecture of the bicycle family in a fully collapsed format, which is indicated by the visible elements and their index numbers. Especially for large graphs it can be very useful to create an initial overview over architectures by filtering out details in the model, without taking away any existing interfaces. The same generic structure can be expressed by analogy with a generic node-link diagram. To limit the discussed risk of having overlapping elements and connections in large and dense graphs, Model (c) narrows the representation of interfaces to the essential aspects. Hence, part-of-structures, kind-of-structures, and constraint links are expressed as previously described, leaving out redundant connection types (dashed arrows). Engineers can benefit from the graphical advantage of quickly identifying patterns and following important paths in the model (Requirement F2), without losing the required understanding for the present interfaces. The context of interfaces is preserved by using the original naming of all elements, which may be particularly important when investigating the cause of collaborations between two components (Requirement 3-4).



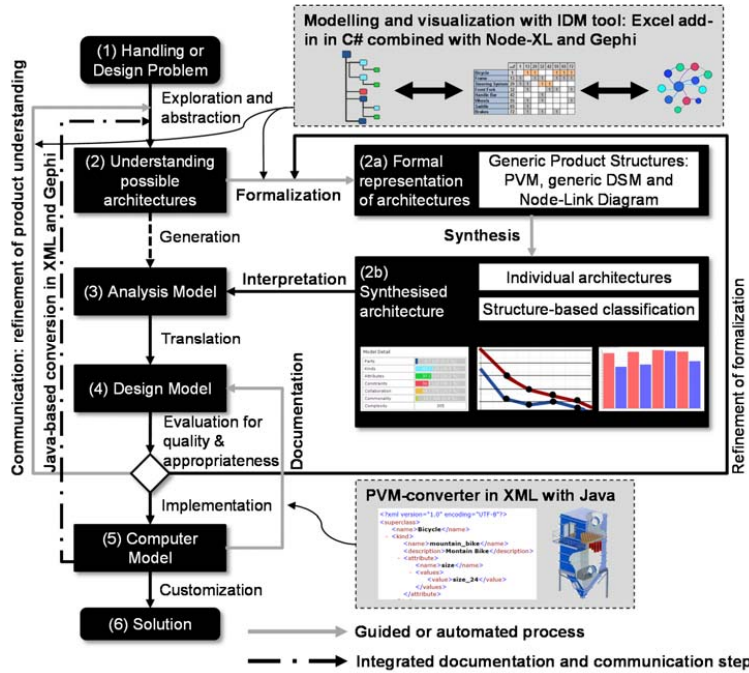
**Fig. 4: Different views of a generic product structure, (a) generic DSM (partly collapsed), (b) generic DSM (collapsed), (c) generic node-link diagram**

The next section presents a method to support product family architecture design and customization based on the requirements in Sect. 3.3. To validate it's applicability of a real case, the method has been further tested in an empirical architecture design problem.

#### 4 Applying a proposed formal synthesis method

To demonstrate a proposed approach, a case study was conducted on an industrial product architecture design and customization process at a major provider of plant and machinery applications. The collaboration with the company was established throughout 2013 the beginning of 2014 and involved several semi-structured interviews lasting between 1 and 2 hours as well as half-day workshops with a team of domain experts, two engineers and one IT expert. The domain experts are part of a larger physically disconnected team, which is responsible for the coordination of the architecture design and its implementation in a configuration system. In addition, full access was given to architecture models of selected product families and their development over a period of 12 months. The objectives for the study were (1) to identify the major concerns for the architecture design and implementation process and (2) to address them with a new approach for generating architectures through the formal synthesis method proposed in Sect. 3.





**Fig. 5: Proposed method to support product family architecture design and customization**

#### 4.1 Documenting and communicating implemented architectures

##### 4.1.1 Consequences of the informal approach

At the beginning of the case study, the company had employed an informal approach as described in Sect. 3.2. In response to an increased market demand for a rapid and robust customization, the company has been implementing a growing part of their product line into the commercial configuration system Tacton (Tacton Systems, 2014). By the end of 2013, more than 30 different product families of highly customizable industrial applications, e.g. conveyors, pumps and valves, have been used by product managers and technical salesmen internally to support customers in specifying their own product requirements. Comparable to other modern configurators, the software provides an object-oriented development environment as described in Sect. 3.4.3 for the design of generic architectures. To facilitate the understanding of the architecture, the computer models may be complemented with comments and technical or illustrative pictures. A representative product family architecture consists of several thousand interconnected elements and may include components that are produced internally or sourced externally by sub-suppliers. The architecture design is generally organized as an incremental process with regular iterative steps and requires the latest architecture to be used as a starting point for the new solution. The objective of the design work typically involves considerations for how to increase the reuse of common parts, while maintaining the necessary product variety or simply for how to comply with changing legal requirements. The lack of a formal and/or integrated computer support forces the organization to use a considerable amount of resources for designing and coordinating developed architectures. Since the computer models per se can neither be extracted nor visually displayed, design

initiatives have to be compared manually against the implemented architectures within the configurator. Moreover, both product managers and engineers find it difficult to verify if a committed design objective, e.g. to increase modularity of certain sub-assemblies, has actually been obtained. Even if substantial rework may be done to achieve this goal, the informal approach provides no method to demonstrate any positive evidence pointing towards the obtained result. In consequence, the insufficient control mechanism of the informal approach increases the risks for delayed product launches and inconsistent architectures.

#### *4.1.2 Applying a proposed documentation and visualization strategy*

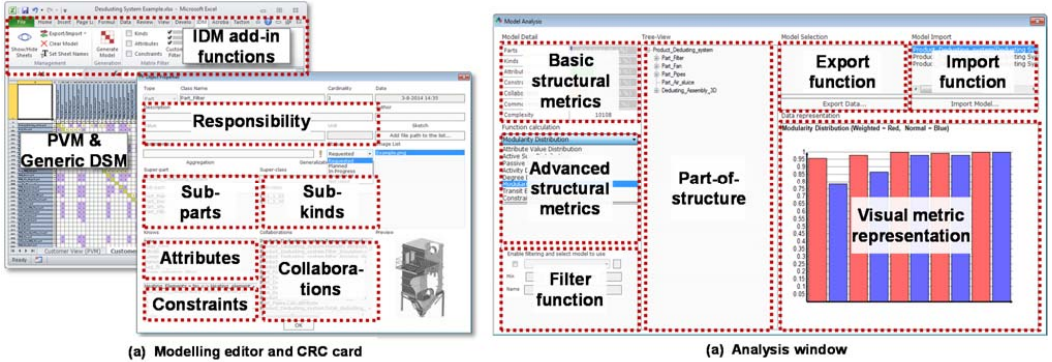
Being aware of this challenging situation, engineers and configuration software experts are pressured from several directions. They have to improve their productivity when designing and implementing architectures and to provide more transparent planning reports to the product management about their progress. This may be achieved by the proposed method illustrated in Fig.5. The described method proposes a pragmatic solution, which allowed to be implemented and tested within the limited time the study. Comparable to many other computer systems, the employed configurator allows by default to save the computer files in the Extensible Markup Language (XML). The XML standard is a text-based format which is frequently used to represent machine-readable structured information, such as documents, configuration status and invoices. Due to its simple and well organized structure, it has been widely-used to share context specific data between programs and people, potentially enabling small models to be understood without any additional software support (XML Working Group, 2010). These XML files created by the configurator contain the encrypted product family architecture of the computer model along with other program specific information. This suggests that the computer models created in Tacton can with relatively little development effort be decoded or converted in a legible modelling format using XML. However, as no XML standard per se is capable of representing generic architectures, a format was created which resembles the discussed PVM notation in Sect. 3.4.3. This was done using a self-developed Java-based application called 'PVM converter'. The application utilizes simple data mining techniques to decode the relevant information within the configurator files and to restructures them into the PVM format. An example of an XML-based PVM file can be seen in Appendix A. The illustrated XML syntax uses the integrated identifiers from the XML language to express part-of-structures, kind-of-structures, attributes and constraints. Apart from documenting the architecture of the computer model alone, the application complements the architecture with comments and path references to pictures which have been included within the knowledge base of the configuration system.

To obtain consistent design models and to communicate them effectively to various stakeholders, the created XML-based PVM models need to be expressed graphically with the discussed grammar methods. Since no dedicated software tools hitherto exist for creating the required generic architectures, a modest solution presented in Fig. 5 is to use of the capabilities of existing open source software and to adjust it to the context specific requirements. This has been realized through an IDM application, a Microsoft Excel add-in which has been developed in C#. The IDM software is used to generate semantically correct PVM and generic DSM models out of the previously created XML-based PVM model. The software has been further combined with the freeware visualization software NodeXL and Gephi, which are two very frequently used tools for studying social networks with node-link graphs (The Gephi Consortium, 2014; The Social Media Research Foundation, 2014). An export function within the IDM software has been developed to ensure the consistency of the generic structure. It converts the XML-file into the discussed convention of node-link diagrams and exports it automatically into the relevant freeware formats, e.g. csv or .gephi. A major advantage of utilising widely accepted standard software is that the obtained solution may be established with relatively low development costs. Furthermore, as no or little changes are made to the existing IT infrastructure in the company, the obtained solution is more likely to be accepted by the stakeholders.

The documentation and communication process may alternatively be combined into one integrated step, so that any user of the configuration system can directly share and discuss the latest version of a particular architecture which is being run within the configurator. As displayed in Fig. 5 the process has been realised by integrating a web-based function within the UI of the configurator, which when selected encodes the underlying computer model first into the described XML-based PVM file and subsequently decodes it into a node-link graph in form a svg- or pdf-based Gephi model. For an industrial company offering a variety of custom tailored products the automatic visualization of the entire generic structure proved to be very valuable in praxis. Product managers and technical salesmen using the configurators are typically very experienced with the provided products. Having a method which allows them to instantly communicate the architecture in use graphically through e.g. a web browser significantly increases the transparency of the achieved solution and eventually enables the consideration of a larger amount of product experience into the design process. Furthermore, if used externally, the method facilitates companies to engage their customers in co-creating new product functionalities and thereby to utilize external resources to drive their innovation processes (Martínez-Torres, 2013). Appendix B displays an example of an automatically created generic architecture of a dedusting system provided by the company. The graph shows a major section of the entire family, which in total consists of roughly 3000 elements. The product is installed in production environments exposed to extreme dust and dirt to keep critical manufacturing areas clean during operation and maintenance. In praxis this is being achieved by creating a negative pressure in the production equipment in order to prevent that generated dust disperses to the surroundings. The major building blocks are illustrated by the shaded areas in the model and include a fan and a filter system, several pipes, as well as an air sluice.

#### *4.2 Formalization and synthesis of the architecture design*

With the described documentation and visual communication of the computer model, the graphs are being used to create an understanding of the design problem and to narrow the development effort to the relevant aspects. The design process may be supported by the IDM software. Part (a) in Fig. 6 shows the modelling environment of the IDM tool, where equivalent to the guided know-ledge base editor of modern configurators (Liao, 2005), the user is assisted in creating valid architectures inter alia by following the in Sect. 3.4.3 discussed generic syntax. Data mining techniques have been further implemented in the software to guide the user in formulating feasible constraints and to consider the discussed aspects of encapsulation. To abstract the model towards the particular design problem, domain experts may choose to collapse or filter out unessential elements. CRC cards are automatically generated and include the implemented pictures and comments of the computer model. To add additional elements, the desired parent class is selected and element details are added in an automatically generated CRC card. Besides, the cards are used to describe additional information about the implementation status of the model (e.g. in progress or implemented) and the responsible domain expert for the particular object. In large design projects this particular feature can be very useful, as it helps project experts in keeping track of the development work and managing the responsibilities of tasks. Depending on the user's preferences, the architecture can be designed within both, the PVM or the generic DSM notation, where furthermore the user can switch dynamically between the IR/FAD and IC/FBD convention of the matrix (see Sect. 3.4.1). Eventually, to synthesize feasible architectures within a wider physically disconnected team of domain experts, each architecture may be communicated using the generic models in any of the three grammar graph techniques.



**Fig. 6: IDM software tool showing a collapsed generic DSM model and a CRC card (a) and the analysis window (b) on the example design problem**

#### 4.3 Interpretation and refinement of synthesized architectures

To support domain experts in comparing architectures of different products or selecting between alternative ones of the same product, each model may be evaluated quantitatively using a set of metrics. A metric can appraise a specific aspect of an architecture in order to evaluate a quality which corresponds to any lifecycle objective of the product (Huang, 1996). Measures addressing product architectures typically include aspects of variant-oriented design (see Sect. 2.1), e.g. product complexity (Sinha and de Weck, 2013), modularity (Sosa et al., 2007), or communality (Thomas, 1992), and may in combination or alone access the considered design problem. However, since the majority of metrics proposed in literature are based on graph-theoretical characteristics of social networks (Bounova and de Weck, 2012), they need to be adjusted to the convention of generic structures for product families. Eleven of them are described in Table 2 and refer to their impact on the design work of the entire architecture of a family or to a chosen sub-section A. Metrics 1 to 4 in the table show basic characteristics of the architecture, e.g. the number of parts and variants in a model, while metrics 5 to 11 indicate the related structural properties. The measures may be used by domain experts to explore the synthesized results towards a preferred solution. The information gained from the metrics can be presented visually with commonly used chart formats, e.g. bar charts, and may help to explore structural patterns or 'interesting' architecture areas. This may be supported either by listing the values unsorted within the charts in the sequence of the index numbers in the model (see Sect. 3.4.1), or by showing them with an ascending or descending order against an absolute scale, e.g. time. This method is realised within a developed analysis tool for the IDM add-in. Part (b) in Fig. 6 displays a screenshot of method applied on an example problem of the dedusting system, where the weighted and normal modularity of the major building blocks have been graphically displayed. The proposed interpretation technique was used by the domain experts on a variety of design problems, where for example the (structural) complexity of architectures could be reduced explicitly. This was achieved by abstracting the design problem to building blocks with higher potential for modularity improvements. The suggested design alternatives could then be evaluated iteratively with regard to their structural impact on the overall architecture, potentially leading to higher overall design quality.

Metric	Formula/ normalized by	Description	Normalized by
1 Parts	$n_p(A) = \sum_{i=1}^n p_i$	More parts require more design work (Hodday 1998): the sum of all parts $p_i$ in architecture (section) A containing $n$ elements	$n$
2 Kinds	$n_k(A) = \sum_{i=0}^n k_i$	Higher variety requires more design work (Martin et al. 2002): the sum of all kinds $k_i$ in architecture (section) A containing $n$ elements	$n$
3 Attributes	$n_a^{(u)}(A) = \frac{\sum_{i=1}^{n_p} \left( \sum_{j=0}^{n_g} a^{(g)}_{ij} + \sum_{t=0}^{n_v} a^{(v)}_{it} \right)}{a^{(u)}_i}$	More functionality requires more design work (Sinha et al. 2013): the sum of all unique attributes $a^{(u)}_i$ in architecture (section) A containing $n_p$ parts, with all generic attributes $a^{(g)}_{ij}$ and all variant attributes $a^{(v)}_{it}$	$n$
4 Collaborations	$Col(A) = \sum_{i=1}^{n_p} c_i$	More interfaces require more design work (Sosa et al. 2007): the sum of all collaborations $c_i$ in architecture (section) A containing $n_p$ parts	Maximum possible degree $Col(A)_{max} = n_p * (n_p - 1)$
5 Commuality	$Com(A) = \frac{\sum_{i=1}^{n_p} \left( \frac{\alpha_i}{\sum_{l=1}^{n_p} (p_l \sum_{j=0}^{n_g} a^{(g)}_{lj})} \right)}{\sum_{i=1}^{n_p} (p_l \sum_{j=0}^{n_g} a^{(g)}_{ij}) + \sum_{i=0}^{n_k} (k_l \sum_{j=0}^{n_v} a^{(v)}_{ij})}$	Higher commonality requires less design work (Jiao et al. 2000): the ratio between all common objects and their properties $\alpha_i$ (all parts times their generic attributes) compared to all objects and their properties (all common objects plus all kinds times their variant attributes) in architecture (section) A	Maximum possible degree $Com(A)_{max}$ for $n_k=0$ or $n_v=0$
6 Complexity	$C(A) = n_p(A) + n_k(A) + Col(A)$	Higher (structural) complexity requires more design work and communication effort (Prasad, 1998); it is based on number of components, their variety and interdependence (Gerald et al. 2011): the sum of all parts, kinds and collaborations in architecture (section) A	-
7 Active sum	$As(A) = \sum_{i=0}^n l^{(a)}_i$	Parts with high active sum are more significant in design (Lindemann et al. 2009): the sum of all interfaces $l(a)$ that emerge from a part	-
8 Passive sum	$Ps(A) = \sum_{i=0}^n l^{(p)}_i$	Parts with high passive sum are more influenced in design (Lindemann et al. 2009): the sum of all interfaces $l(p)$ that affect a part	-
9 N-modularity	$N_m(A) = \frac{\sum_{i=1}^{n_m} l^{(m)}_i}{\sum_{j=1}^{n_o} l^{(o)}_j}$	Higher modularity facilitates variety and concurrent design and maintenance; modules are tightly connected components inside a cluster and loosely connected to others (Sosa et al., 2007): the normal ratio $N_m(A)$ between all interfaces $l(m)$ within a selected section $n(m)$ compared to it's interfaces to other parts $l(o)$ in architecture (section) A containing $n(o)$ parts	-
10 W-modularity	$W_m(A) = \frac{\sum_{i=1}^{n_m} l^{(m)}_i}{\sum_{j=1}^{n_o} l^{(o)}_j}$	Modularity may be weighted, to account for multiple connections between two components (Gershenson et al., 2004): the weighted ratio $W_m(A)$ between all interfaces $w(m)$ within a selected section $n(m)$ compared to it's interfaces to other parts $w(o)$ in architecture (section) A containing $n(o)$ parts	-
11 Constraint active sum	$Cas(A) = \sum_{i=0}^n l^{(c)}_i$	Constraints with high active sum are more significant in design (after Lindemann et al., 2009): the sum of all constraint links that emerge from a constraint $l(c)$	-

## 5 Conclusion

Mass customization provides a promising concept to respond rapidly to individual customer needs. It requires from manufacturers to effectively design, implement and maintain suitable product family architectures in configuration systems, which are then used to efficiently support the customization process. This paper has investigated the application of related modelling methods and formal computer-based approaches to facilitate this process. In particular, the paper argues that architectures can be presented explicitly through appropriate grammar graphs which consider common generic modelling standards if the UML language. This systematic documentation and visualization of architectures allows the integration of a widespread internal product expertise as well as stronger customer engagement. Moreover, the quality of architectures may be evaluated objectively through computational structural analysis methods, making any assumptions about the obtained solution transparent and thereby accessible. The usability of the methods has been demonstrated on an industrial case study of a major

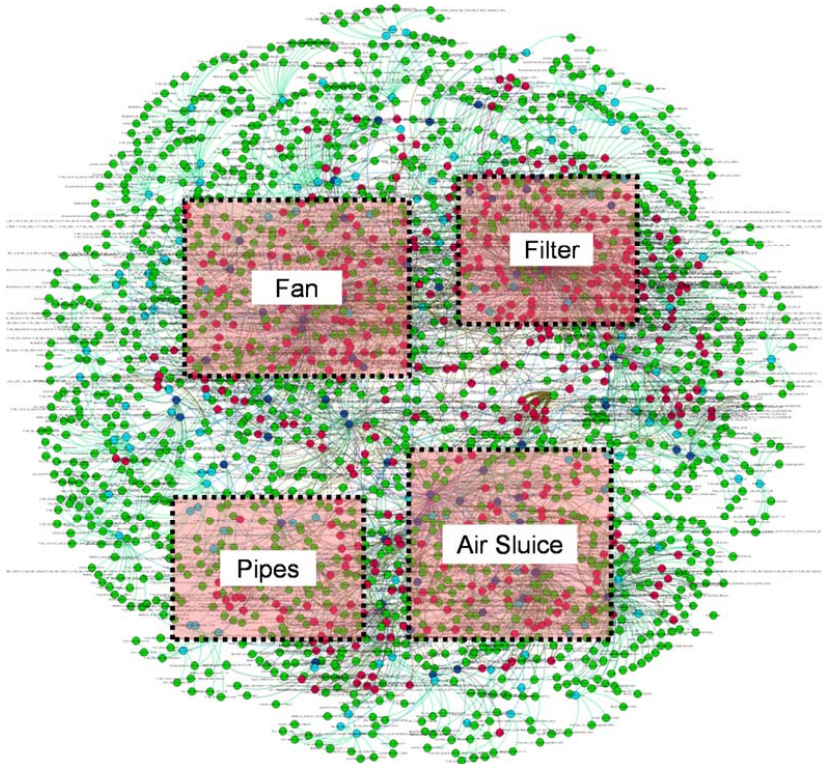
plant and machinery provider. The capabilities of a state-of-the-art configurator have been complemented with automatically generated grammar graphs. Besides, the architecture design process was assisted through a computer-based modelling and analysis method consisting of guidelines and visually represented structural metrics.

While the proposed formal computational approach has led to a number of benefits for the case company, the applied methods have been specifically designed to fit the particular needs of the studied industrial praxis. Future research might consider addressing these limitations and thereby extending the relevance of the presented methods. Specifically, the discussed documentation techniques may be applied to a variety of commercial configuration systems. In addition, a dedicated modelling and analysis system may be developed to obtain a more stable and scalable software solution.

## Appendix A. Illustrative XML-based example of a PVM

```
<?xml version="1.0" encoding="UTF-8"?>
<superclass>
  <name>Bicycle</name>
  - <kind>
    <name>mountain_bike</name>
    <description>Mountain Bike</description>
    - <attribute>
      <name>size</name>
      - <values>
        <value>size_24</value>
      </values>
    </attribute>
  </kind>
  - <constraint>
    <name>Frame.wheel_size = Wheels.size</name>
    <description>Frame.wheel_size, Wheels.size </description>
  </constraint>
  - <part>
    <name>Frame</name>
    <cardinality type="integer">1</cardinality>
    - <kind>
      <name>ibis_carbon</name>
      <description>Ibis, Mojo carbon </description>
    + <attribute>
```

## Appendix B. Generic node-link diagram showing the discussed design problem of a degusting system



(Gerald et al., 2011; Gershenson et al., 2004; Hodbay, 1998; Jiao and Tseng, 2000; Martin and Ishii, 2002; Sinha and de Weck, 2013)

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## APPENDIX K

# Managing complexity of product mix and production flow in configure-to-order production systems

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## Abstract

In designing configure-to-order production systems for a growing product variety, companies are challenged with an increased complexity for obtaining high productivity levels and cost-effectiveness. In academia several optimization methods and conceptual frameworks for substituting components, or increasing lot sizes and storage capacity have been proposed. Our study presents a practical framework for quantifying the impact of a two-way substitution at different production stages and its impact on storage and machinery utilization. In a case study we quantify the relation between substitution, lot sizing and capacity utilization, while maintaining the production capacity as well as the external product variety.

**Keywords:** Complexity Management, Mass Customization, Inventory Control

## Introduction

One of the major challenges that companies face in the latest decades is the potential of increasing their product portfolio by sustaining a low level of complexity. Mass customization has succeeded in bridging the gap between the mandatory market requirements and the need for product differentiation. In order to obtain a competitive advantage, companies have been significantly expanding their product variants to the market, causing an inevitable complexity in product architecture, assembly and supply process (Hu et al., 2008). Mass customization principles serve this need by creating unique products with nearly mass production efficiency. In a Configure-To-Order (CTO) production environment the product differentiation can take place on several different levels, from modules to final assemblies. Product and production complexity increases as companies are trying to fulfill customer demands in terms of product variation so as to strengthen their competitive advantage. However, researchers have shown that not every variant contributes positively to the net revenue of the company. Moreover, the



profitability of each product variant is in addition related to the production flow, in terms of lot size and Stock Keeping Units (SKU) (Yücel et al., 2009).

One of the suggested approaches to assess the impact of the increasing product mix on the firm's performance is to investigate how variety complicates the assembly process and supply chain operations (Braglia et al., 2006). ElMaraghy et al. (2003) introduce two factors of increasing complexity, firstly the number and diversity of features to be manufactured, assembled and tested, and secondly, the number, type and effort of the tasks required to produce the features. Yet traditional production and inventory planning related research has concluded to an integrated model optimizing the values for the process mean, quantity, and production lot size (Al-Fawzan et al., 2002). While both aspects are relevant when investigating the impact of increasing product differentiation, their interrelated impact has seldom been discussed. This research therefore studies how both reducing product portfolio complexity as well as increasing production flow and inventory utilization can contribute to the overall performance of manufactures offering custom tailored products.

The remaining paper is structured as follows: After having introduced the research topic, section 2 discusses the related literature and builds the conceptual framework for the proposed approach. Section 3 substantiates the research aim and methodology, while in section 4 describes the results from testing the suggested approach on a case study. Finally, a conclusion of the research outcome is given in section 5.

## **Theoretical Background**

### *Complexity and Product Architecture*

In previous years numerous studies have been conducted aiming at analysing and evaluating complexity which arises in the product range of manufacturing companies. Samy et al. (2012) define complexity as “a measure of how product variety can complicate the production process”. In the same concept Arteta et al. (2004) point out that complexity is preventing a company from changing its organizational structure, processes and products, and it is connected to the interrelationships of the system components. MacDuffie et al. (1996) quantify product complexity to test the impact of product variety on quality and productivity in a LEAN manufacturing environment. Several researcher have performed similar work (Fujimoto et al., 2003, Fisher et al., 1999, Martin et al., 1996), where the focus has been to measure how the production process is affected by product complexity, related to the increasing number of variations. An approach widely used for measuring systems complexity is based on entropy measure (Arteta et al., 2004).

### *Method for ABC differentiation*

The ABC analysis was initially developed by Pareto (Pareto, 1971) has been further used in operations management. The product categorization to A, B, and C products is based on the relative distribution of cost or the usage of the SKUs. The multiple criteria of ABC product prioritization is moreover considering several aspects which the operations management domain have been of great importance for inventory management, such as lead time, substitutability and variability (Benito et al., 1985).

With the rapidly increasing number of variants in the recent years, manufacturers are trying to maximize the variants offering, in order to serves their customers' needs, increase competitiveness and identify the market niche. However, not all variants contribute to the net revenue neither at the same percentage. As a result large product variety does not imply for stable long-term profitability (Koo et al., 2009, Sarkis, 1997), and the ABC product differentiation becomes imperative.

To this end, later studies have shown relations between the ABC product differentiation and the lot size (Yücel et al., 2009) or substitution (Hsu, 2005).

### *Substitution at different stages*

Substitution is a method which complies with Mass customization principles and platform designs. Current research has classified two aspects of substitution: firm-driven and customer-driven. This research is primarily focus on firm-drive substitution at a module level, as the customer-driven substitution cannot be controlled. The sales person, or even the customer himself, decides on the substitution of one final product with another (Zhou, 2013).

Zhou and Sun (2013) have developed a model to determine the optimal component quantities in an assembly-to-order system with component substitution, so as to maximize manufacture's profitability. Several researchers have considered product substitution based on the demand. Yaman (2009) creates a model in order to define the lot sizing problem by substituting the products of low quality with high quality products. On the other hand, Hsu et al. (2005) develops algorithms in order to define the lot size between two products. The product in lower demand can substitute the product higher demand, with or without the need for redesign.

### *Lot size and Sales Demand*

Masuchun and Masuchun (2008) have created a model to determine the optimum lot size in order to match the production flow and the customers' demand. Bottleneck machines affect the production rate, and in order to maximize efficiency the lot size should be large (Koo et al., 2009). Furthermore, Yu (2012) examines the production lot size in relation to the demand. Benjaafar and Gupta (1998) are suggesting that the number of final products and the lot size are commensurate, however they results are based on the assumption that the production facility is able to expand or change.

### *Research aim*

Based on the previous literature review, this paper attempts to contribute to the quantification of the relationships between product complexity and lot size. The factors taken into consideration are product common features on module level, substitution on component level and lot size determination. Drawing upon the basic idea of mass customization, we present a concept where the final product variation is not to be decreased and for short and mid-term planning -the production facility is considered under the limitation of neither expansion nor change. The ABC categorization approach is used to determine the appropriate components' substitution strategy, as well as the lot sizing.

The purpose of this paper is to examine the production flow optimization by adapting the product assortment. The previous research has shown the dependencies between the two aspects, however in this paper we examine them from another perspective. The product mix is our variable, while the operation flow is standard. Due to limitations on expansion of stock and number of machinery, the impact of the product assortment adjustment is used to measure productivity. Additionally, production size should not be affected.

### *Proposition 1 (P1)*

Substitution on a module and component level contributes to improving of the production flow and capacity utilization of machinery and inventory.

## **Suggested approach**

### *ABC product categorization*

Based on the Pareto theory (Pareto, 1971), an ABC analysis on component level is performed, where the sales volume of finished products is used to differentiate between the categories. In detail, 80% of the sales correspond to fewer products, which are considered as A products. Similarly, 15% of the sales volume corresponds to the B products and 5% to the C products .

Sales values are often stored on a final product level. To be able to perform the ABC categorization on components level the variance decomposition structure is used. Each finished product is broken into its different components, based on the listed Bill-of-Material (BOM). The sales volume of the finished product indicates whether the product is A, B, or C. Through the variance decomposition analysis, the sales volume of the components is set in relation to the sales volume of the finished product.

The variant categorization is to be further used in order to implement the two-way substitution.

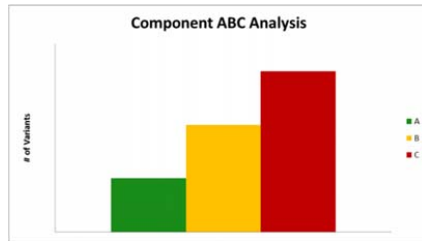


Figure 1 - ABC analysis on component level

#### *Substitution and process flow*

The second aim of the research methodology is to implement a substitution method in order to measure the impact on the machine and stock utilization, which is related to the lot size. The suggested approach is based on the theories discussed in the literature section; however it goes one step further by combining the substitution methods for which a two-way substitution method is proposed.

The first step of this method focuses on utilization of the C component variants kept in stock, in order to increase their utilization and free up the stock capacity. C components have by definition lower sales volume. They are taking up more space in the stock and for a longer time period, than the A components, which are used frequently. Moreover the average lot size of the C products is small, which is related to increased changeover and set up times, implying for increased cost and complexity in the production flow. The quantification of the stock capacity is calculated based on the average number of pallets occupied by each component in stock. The machine utilization is calculated on the number of components produced per run.

According to the suggested method, the C components kept in stock would replace the similar components in the A products. The main challenge is to identify which C variants could substitute the A variants in the final product assembly, without compromising neither the quality nor the specifications of the finished product. This first method can be seen a short-term suggestion, with a focus on achieving immediate impact in production

The second step of the substitution method proposes a long-term solution, in which the A components substitute the C components in the final product. This results in out phasing the C components of limited utilization, which leads to an increase of the stock capacity. At the same time the replacement of C components enables higher production and stock utilization of the A components, as manufacturers can plan with higher lot sizes. This action results in optimizing the machinery utilization, especially for those machines that are potentially creating bottlenecks. The optimization is succeeded by reducing the change overs and the setup times for producing A components. In relation to the stock capacity, the substitution of the C components has positive effects, as the slow moving pallets with C components are replaced by pallets with A components.

This step of the suggested approach identifies the relations between the substitution and changes in the lot size, and their impact on the production process.

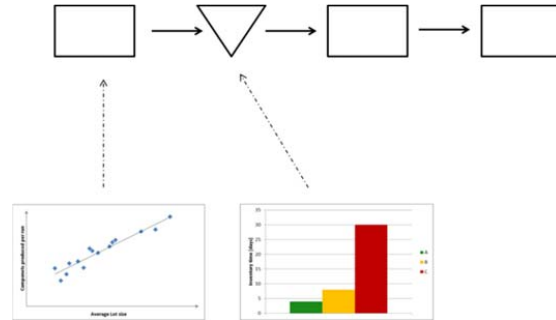


Figure 2 - Impact of lot size on machine utilization and stock

#### *Lot size and capacity utilization*

The third step of the suggested approach, builds upon the previous and examines the relation between lot size and machine utilization. The reviewed theories indicate a connection between the lot size and the optimization of output of each machine in the production process. The bottleneck machines are of great importance in this stage. Additionally, the lot sizing is related to the second step of the substitution method (A components used for C variants). As the total volume of the A components increases, the manufacturer can plan with a higher average lot size of the process flow will. The examined relation is illustrated in the following figure.

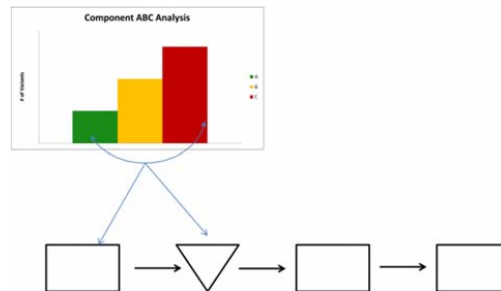


Figure 3 - Impact of substitution strategy to the process flow

#### **Research Methodology**

Based on a literature study, the paper first examines the interrelation between the product mix and the production flow in terms of complexity. Mass Customization principles are highly related to the dependency between complexity management and profitability optimization ( Zhang et al., 2007). Blecker et al. (2006) suggest analyzing the interrelation between product variety and process domain. In order to create an understanding of their relative importance with respect to the area of complexity

management, a case study of a manufacturer offering configure-to-order (CTO) products is performed. The data sample regards all product orders and the related daily activities in machine and inventory utilization for a one-month period. This in depth analysis follows the proposed methodology and hence allows relatively high validation of the acquired information (Yin, 2003).

### Case study

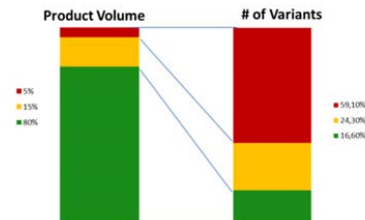
In order to test the proposed framework and quantify the production flow optimization by adapting the product assortment, a case study of a manufacturer in the CTO industry is performed. The company produces plaster gypsum boards for the construction industry. The final product consists of several layers (components): plaster façade (with or without paint), gypsum board, light reinforcement, heat and fire insulation. The challenging aspect of this specific case study is the lack of expanding options, especially on large scale such as expansion of the production site or the warehouse, purchase of supplementary machinery. As a result the chosen case study is selected as an example where the optimization of production flow and capacity utilization could only be achieved by the examined proposition. Empirical data were gathered on a daily basis for one-month period, and the forecasted increased demand in a two-years' time period. The data sample regards all product orders and the related daily activities in machine and inventory utilization. Data collection included also the modular structure of the products in terms of assembly processes and stock capacity utilization.

In order to implement and evaluate the suggested approach on this case study, the analysis of the current state is to be used as a baseline. The following table summarizes the data required for the analysis.

*Table 1- Research Protocol*

Data needed	Quantification
1. Bill of material of finished products Sales volume of finished products	ABC analysis on the component level Substitutability on the component level
2. Average lot size per run per component Production per run per component	Calculation of the optimal relation between lot size and machine utilization
3. Number of pallets with C components in stock Number of pallets with A components in stock	Stock utilization caused by substituting C components with A

Implementing the suggested approach, an ABC analysis was performed to the finished products, and subsequently to the components. The following figure illustrates the relation between the volume of the finished products and the number of variants, based on the ABC product differentiation made after the related data was acquired.



*Figure 4 - Percentage of finished products and of their variants*

The analysis of the current state constitutes the first step of the proposed framework. to the historical data on sales volumes helps to estimate the current market trend and indicates in which steps of the production the capacity exceeds the maximum level, both in machinery and stock keeping units. The current state is used as a baseline scenario and serves when evaluating the alternative solutions. The first scenario suggests substituting C variants with A variants on component level, i.e. at an early stage of the production process. In our case study, the results from the early component variant decrease through substitution lead to a reduction both in stock capacity requirements, as well as in the bottleneck machines. The following figure shows the average time for the A, B, and C components kept in stock. C components have in average 20 times more inventory time than A components. Due to this ratio, by eliminating C components the stock capacity will increase rapidly.

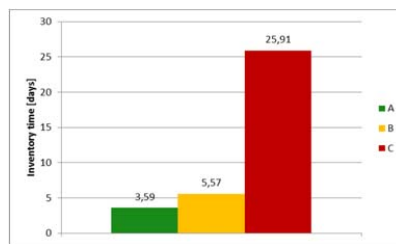


Figure 5 - Duration of stock keeping per ABC component

Based on the number of pallets in stock for each component, the following figure clearly illustrates that C components require higher capacity, due to the fact that they are slowly moving. C components take overall 43% of the available storage space. By substituting the C components with A, the storage space will become available for A components, which will also lead to increase the production of A components.



Figure 6 - Percentage of stock capacity per ABC component

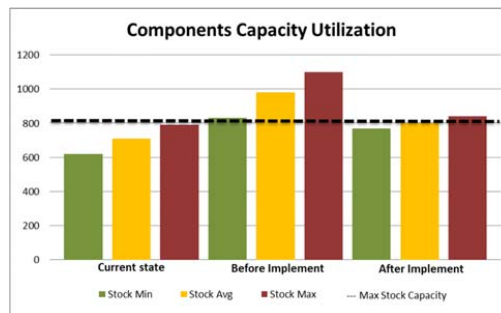
The second scenario consists of a combined short and long term solution, with two-way substitution at a later stage in the production process. The first step suggests the substitution of A variants by C variants, in order to reduce the number of the slow moving C variants in stock. This approach could be applied due to fact that the substitution will not jeopardize the quality of the final assembly, as for the

case products the only difference between the two variants is the size of components (length, width). As a result the variation of the final products would not be affected. The second part of this scenario is the long term suggestion, which introduces substitution of C components on the final products by A. The substitution takes place at a later stage of the final assembly. The outcome of this scenario is a great reduction of stock capacity requirements, as the slow moving C variants are no longer produced. This strategy results in freeing up the space occupied by C variants and providing more space for the widely used A variants.

*Table 2 - Summary of substitution strategies*

	C plates for A cores	A plates for C cores	Both strategies
Total variants	618,8	618,8	618,8
Total eligible c plate variants	137,8	24,7	149,5
Total variants %	28,9%	5,2%	31,4%
Total pallets	83,96	14,97	92,70
Total pallets %	10,2%	1,8%	11,3%
Total cost	€ 192.649,05	€ 181.933,90	€ 374.582,95
Cost per pallet	€ 2.982,82	€ 15.796,66	€ 5.252,86

The following figure illustrates the capacity utilization for the components kept in stock. Three scenarios are compared, the current situation, the future state (in two years) without making any changes and the future state after implementing the suggested approach. The result shows that by substitution of C components with A, the Average stock capacity will not exceed the maximum limits.



*Figure 7 - Capacity utilization for components*

With reference to the machine utilization, the following figure illustrates the relation between the average lot size and the number of components produced per run. The tendency is quantified to the following formula:

Equation (1):  

$$y = 5,0433x + 123,36$$

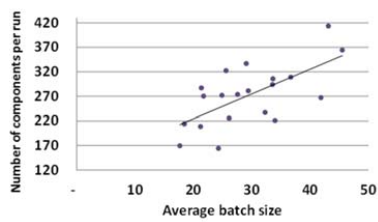


Figure 8 - Relation of lot size and production

The figure above indicates that the machine utilization benefits from the increasing lot size. The number of components produced per run is directly depended on the lot size. This implies that for the A components, where the production is high, the optimum lot size should be increased.

### Discussion and Conclusions

With mass customization academia has addressed a growing demand for custom tailored products. From a solely mass production environment, manufacturers have been utilizing CTO strategies to realize higher product variety. In designing CTO production systems several considerations are made with regard to production flow, storage and machinery optimization. One way of balancing the right level of variety throughout production is by managing the complexity of the system.

With this study we have presented a practical framework for reducing the complexity level at different stages in production. An ABC categorization based on sales volumes has been used to distinguish between slow running and fast moving components, while BOM structures of final products have been analyzed to identify the sales volumes components and modules. A two-way substitution has been used on different stages during production and its impact on lot sizing and capacity utilization for machinery and storage space has been discussed. The framework was tested on a case study, where a CTO manufacturer has been challenged with an increased customization demand and limited production capacity. Based on performed analysis, the impact of a number of complexity reduction scenarios was quantified in relation to total production cost and utilization.

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Handling the customization-responsiveness squeeze in engineer-to-order industries comprises several risks, including rising complexity and reduced profits. Mass customization has been recognized to offer enormous opportunities for its adequate management. The objective of this PhD project was to define general capabilities for mass customization and to develop an embracing concept for their enhancement. Based on insights from eleven case studies across different industries, the concept was detailed into product family architecture design and complexity management methods, where several advantages and further improvements for both industry and academia were emphasized. Furthermore, an executable tool termed Integrated Design Model was developed, to apply a proposed formal and computational structural analysis on a practical design problem. The tool employs aspects of visual analytics and can be used in connection with state-of-the-art configuration systems to create an interactive and insightful modelling environment.

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